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Modeling the Magnetic Field of the Virgo Cluster For Axion Like Particle Search in Gamma Ray Energies

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Axions are hypothetical pseudo Nambu-Goldstone bosons which arise from spontaneous symmetry breaking of the Peccei Quinn Symmetry, which in turn is a proposed solution to the Strong CP problem. Axions and axion-like particles (ALPs) are also dark matter candidates as they only interact gravitationally, and through weak coupling with the Standard Model. Weak coupling with the photon leads to the photon-ALP oscillation phenomenon which is expected to occur in the presence of astrophysical magnetic fields. For light ALPs we expect to find signatures of these oscillations at gamma-ray energies. Active Galactic Nuclei (AGN) in large galaxy clusters are good observational candidates to attempt to observe these oscillations in the relatively strong cluster magnetic fields. In this study we model the magnetic field profile of the Virgo cluster using Messier 87 and 84 in the cluster, with the intention to probe photon-ALP oscillations. To model the magnetic field, we utilize the open source gammaALPs package framework to create a randomized magnetic field model with Gaussian turbulence. We fine tune the model parameters by calculating Faraday rotation measures along two lines of sight and constraining the magnetic field via these values. We then simulate photon-ALP oscillations for various pseudo-random realizations of the turbulent field. This model is planned to be used to search for photon-ALP oscillations in gamma rays emitted from the Messier 87 AGN. This model may also be utilized for various other studies which require the modelling of this particular magnetic field.

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1. Introduction

The axion is a theoretical pseudo-scalar particle predicted independently by Weinberg [20] and Wilczek [21] in 1978. This prediction was made following the 1977 paper by Peccei and Quinn [13], who introduced a new global symmetry in an attempt to resolve the Strong CP problem. Weinberg and Wilczek demonstrated that this symmetry can be spontaneously broken giving rise to the axion. These particles offered more than just a solution to the Strong CP problem. They also proved to be a major contender to explain dark matter [1, 4, 6]. While the axion is weakly coupled to the Standard Model, it is light and incredibly difficult to detect. Axion-like particles or ALPs are theoretical counterparts of the pseudo-scalar axion. These ALPs are expected to exhibit similar properties as that of the QCD axion, but do not fit within the region of the parameter space which would allow it to solve the Strong CP problem. From the theoretical formulation of axions, there is an inferred expectation of an observable "mixing" of the axion state with photon states in the presence of magnetic fields. This results in an oscillation of the particle between both states. This provides us with an observable phenomenon which we can exploit to attempt the verification of this theoretical particle. The oscillatory nature of axions and ALPs was described by Raffelt and Stodolsky in their 1988 paper [15]. The interaction can be summarized with the Lagrangian $\mathcal{L} = g_{a\gamma}\vec{B}.\vec{E}a$, where $g_{a\gamma}$ is the coupling strength, $\vec{B}$ is the magnetic field, $\vec{E}$ is the electric field of the photon and a is the axion field strength. The photon-ALP oscillation effect can be expected to cause measurable variations in the observed spectra of high energy sources. The high energy photons emitted by the respective source(s) traverse various astrophysical magnetic fields along their trajectory toward our instruments which would cause photon-ALP oscillations [10]. The predicted photon-ALP oscillations would lead to the formation of observable "wiggles" in the spectra. Being able to model the magnetic field accurately will provide us with a means to then accurately calculate photon survival probabilities to model the ALP wiggles. This then allows us to probe and constrain the parameters of our candidate particle, provided we have enough available statistics to fit our model over.

The goal here is to model the magnetic field of the Virgo cluster in order to search for photon-ALP oscillations in gamma-ray spectra of the central galaxy: M87. Messier 87, also known as Virgo A is an Active Galactic Nucleus located centrally in the Virgo cluster. The Virgo cluster itself is located 53.8 ± 0.3 Mly [9] away from us in the Virgo constellation . It lies at the heart of the Virgo Super-cluster, of which the Local Group is also a member.

2. Modelling the Virgo Magnetic Field

Magnetic fields we encounter in nature are generally turbulent, or in simpler terms: chaotic. These chaotic systems pose quite a challenge to model with any reasonable amount of predictability. While the general method we use here follows that of Marsh et al. [8], we choose to use a Gaussian turbulent field model for the magnetic field. Usually the magnetic field is modelled using a cell-like morphology, with the field strength being constant in each cell with a length L_{coh} but the direction of the magnetic field changes randomly from cell to cell. The coherence length is usually taken to be in the order of the size of a galaxy in the cluster which is ≈ 10 kpc. We however use a divergence free homogeneous and isotropic Gaussian turbulent magnetic field with zero mean and variance B^2

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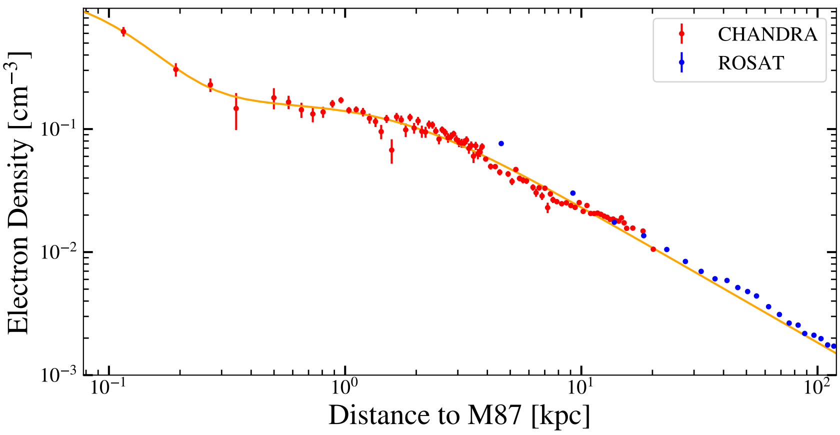

Figure 1: Plot showing the electron density distribution in Virgo from the utilized X-ray data

[12]. We are assuming in this model that the power spectrum of the turbulence follows a power law with wave numbers, $M(k) \propto k^q$ between $k_L \leq k \leq k_H$ and otherwise zero [10]. Further, the Virgo magnetic field itself is modeled as two distinct regions: an inner region and an outer one. We expect the inner region and outer regions to exhibit significantly different magnetic profiles with respect to the change in the matter distribution profile at these different scales. We use $k = -2.9$, $k_L = 0.42$, $k_H = 6800$ and $k = -2.5$, $k_L = 0.42$ and $k_H = 12$ for the inner and outer regions, respectively. In region 1 we pick these values to match the coherence length of 0.2 kpc found in [7]. As for region 2 we utilize values from another cool core cluster [19] as was done previously [8].

We generally expect a variation in the components of the magnetic field $\vec{B}_i$ as a function of the central magnetic field B_0 and with the variation of the electron density $n_e(r)$ radially from the core. The equation used is as follows:

$$(\vec{B})_i = B_0 \left(\frac{n_e(r)}{n_e(0)} \right)^{\eta} \tag{1}$$

To help constrain our magnetic field model for the Virgo cluster we utilize observations made in the X-ray regime. In this case we use data obtained from the CHANDRA and ROSAT telescopes [14, 16, 18]. These are shown in Fig.1 together with a spline interpolation for n_e, chosen such that the electron density is flat for low radii. This will result in a conservative estimate for the central magnetic field.

What is left to be determined are the values for B_0 and η. We follow Marsh et al. [8] and constrain these using rotation measures (RM) along the lines of sight to M84 and M87. These RM values have been extracted in Guidetti [7] using VLA observations of the Virgo cluster. The RM is calculated as a line-of-sight (l.o.s.) integral over the electron density and the magnetic-field component parallel to the l.o.s.,

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2} \int_{l.o.s.} n_e(l) \vec{B}(l).d\vec{l} = \frac{e^3}{2\pi m_e^2} \int_{l.o.s.} n_e(l) B_{||}(l).dl, \tag{2}$$

where e and m_e are the charge and mass of the electron, respectively.

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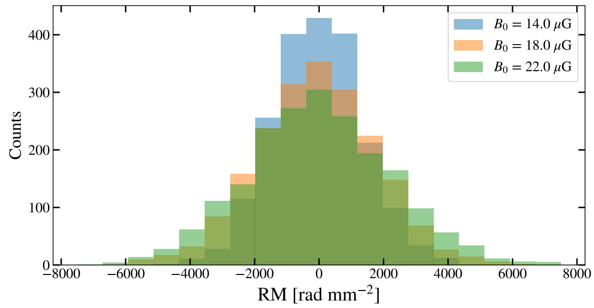
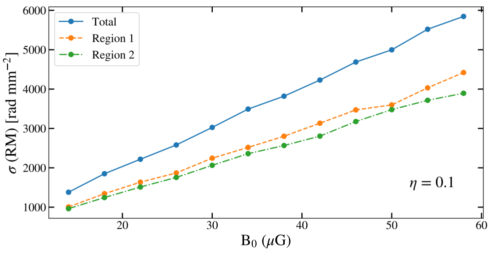
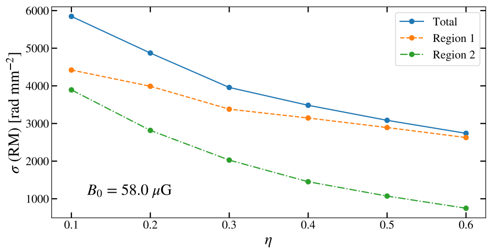


(a) Distribution of RM values



(b) RM vs B_0



(c) RM vs η

Figure 2: Plots illustrating the results of the RM calculations for M87. (a) A sample histogram showing the RM distributions of 3 combinations of B_0 and η values. From the histograms, we calculate the σ(RM) values. An examples for the dependence of σ(RM) on B_0 for a fixed η value is shown in panel (b) and vice versa in panel (c).

We use measurements along two lines of sight: one toward the core and one toward the outer region. In this case, measurements were obtained for both M87 and M84, the former lying at the heart of the cluster and the latter in the outer region. For concreteness, we use the following distances to M84 and M87:16.520 Mpc and 16.830 Mpc [17]. This results in a distance of 535.39 kpc between the two objects. We calculate our RM values along both these lines of sight. We produce 2000 random realizations each of the magnetic field for different combinations of B_0 and η values. This is done using the gammaALPs open source framework [11].

Examples of our RM calculations towards M87 are shown in Fig. 2. The histogram in Fig.2a shows us a spread of the RM values obtained from simulating 2000 realizations. We now calculate the standard deviation of each histogram in this plot for each combination of B_0 and η. The dependence of σ(RM) on B_0 for a fixed value of η is shown in Fig. 2b (and vice versa in Fig. 2c). Our results for σ(RM) for both M84 and M87 over the entire grid of tested B_0 and η values is shown in Fig. 3. The solid and dashed contour lines show the values of constant RM for M87 and M84 respectively. We choose a combination of B_0 and η values which corresponds to an intersection of lines with the most realistic values of the rotation measures for both sources [7, 8]. We expect the RM values of M87 to be between 1000-2000 rad mm^{-2}, while we expect M84 to be between generally quite small. We further limit our choice to the expectation of equi-partition ($\eta \sim 0.5$), as is motivated by Marsh et al. [8]. We finally chose a B_0 value of 34.2 μG after placing all constraints as described.

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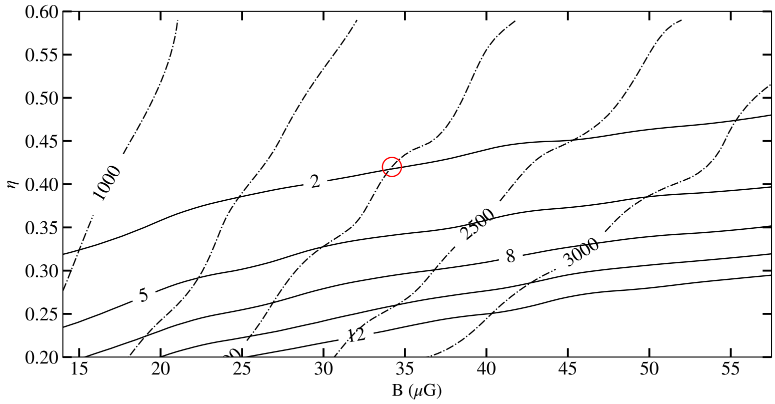

Figure 3: The possible σ(RM) in rad mm^{-2} values of M87 and M84 plotted in a space of B_0 vs η. Circled here is the chosen intersection point of contour lines.

The photon-ALP oscillation effect is expected to leave a signature in the spectra of our source in the form of “wiggles” by virtue of photons oscillating into ALPs and back during their propagation to our instruments of observation. These photon survival probabilities can be calculated, provided we have an accurate model for the magnetic field(s) traversed by the particle. To effectively model the photon-ALP oscillation "wiggles" in spectra, we constrain our model around two free parameters: the mass m_a of the particle and its coupling to the photon, $g_{a\gamma}$. The combination of these parameters establishes which energy ranges we expect the wiggles to appear most prominently in, and thus the ranges which we can probe to constrain these parameters. On the other hand, this means we are limited in our ability to probe the ALP parameter space by the energy ranges which we are able to observe using the instruments at our disposal. We provide the gammaALPs software with all the parameters for our magnetic field model along with the set of mass and coupling values we choose to probe for the particle. The software then simulates the photon survival probability for a specified number of pseudo-random realization of the magnetic field for the specified particle parameters. Here we choose to probe the ALP parameter space between mass values of 10 - 1000 neV and coupling values 10^{-11} - 10^{-10} GeV^{-1}. At these ranges, we expect the "wiggle" features resulting from photon-ALP oscillations to appear in gamma ray energies. This is shown in Fig 4 for the magnetic field realizations of one specific set of parameters. We create such models for every combination of parameters we expect to probe. The resulting models can now be used to fit against real world data and possibly constrain the parameter space further.

3. Results

In order to model the photon-ALP oscillations and their resulting "wiggle" features in high energy gamma rays emitted by Messier 87, we first attempted to model the magnetic field of the Virgo cluster of galaxies, in which M87 is centrally located. We utilize the open source gammaALPs framework to model the magnetic field by first providing it with electron density measurements made using the X-ray telescopes CHANDRA and ROSAT. We used these to calculate Faraday Rotation Measures along both lines of sight, which were then used to constrain the central magnetic

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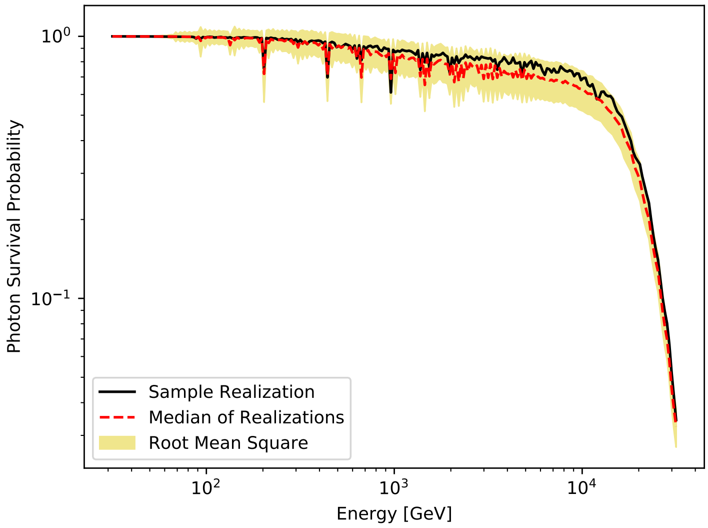

Figure 4: One realization of photon survival probability plotted against the median of all rms value over all realizations (m_a = 100 neV; $g_{a\gamma} = 10^{-11}$ GeV^{-1}).

field B_0 of Virgo. Having fixed B_0 to 34.2 μG, we calculate the photon survival probabilities for the range of ALP parameters which are expected to show oscillation features most prominently in the gamma ray energies. These models can now be applied to real world data sets to search for ALPs. The obtained photon survival probabilities for masses between 10 - 1000 neV and coupling values between 10^{-11} - 10^{-10} GeV^{-1} provide us with models including the "wiggle" features due to photon-ALP oscillations. These wiggles are most prominent in the range of a few hundred GeVs to a few TeVs. This is the ideal range for some of our modern gamma ray telescopes. The HESS telescope has reported observations of M87 in flaring states in the years 2005 [3], 2010 [2] and 2018 [5]. This might allow us enough statistics to effectively probe for these oscillation effects and be able to compare a fit of the ALP model against existing non-ALP models which describe the spectra obtained of M87.

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References

[1] Abbott, Laurence F., and P. Sikivie. "A cosmological bound on the invisible axion." Physics Letters B 120.1-3 (1983): 133-136.

[2] Abramowski, Attila, et al. "The 2010 very high energy γ-ray flare and 10 years of multi-wavelength observations of M 87." The Astrophysical Journal 746.2 (2012): 151.

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[3] Aharonian, Felix, et al. "Fast Variability of Tera–Electron Volt γ Rays from the Radio Galaxy M87." Science 314.5804 (2006): 1424-1427.

[4] Arias, Paola, et al. "WISPy cold dark matter." Journal of Cosmology and Astroparticle Physics 2012.06 (2012): 013.

[5] Benkhali, Faical Ait, Nachiketa Chakraborty, and Frank M. Rieger. "Complex gamma-ray behavior of the radio galaxy M 87." Astronomy & Astrophysics 623 (2019): A2.

[6] Dine, Michael, and Willy Fischler. "The not-so-harmless axion." Physics Letters B 120.1-3 (1983): 137-141.

[7] D. Guidetti, Magnetic fields around radio galaxies from Faraday rotation measure analysis. PhD thesis, Universita di Bologna, April, 2011.

[8] Marsh, MC David, et al. "A new bound on axion-like particles." Journal of Cosmology and Astroparticle Physics 2017.12 (2017): 036.

[9] Mei, Simona, et al. "The ACS Virgo Cluster survey. XIII. SBF distance catalog and the threedimensional structure of the Virgo Cluster." The Astrophysical Journal 655.1 (2007): 144.

[10] Meyer, Manuel, Daniele Montanino, and Jan Conrad. "On detecting oscillations of gamma rays into axion-like particles in turbulent and coherent magnetic fields." Journal of Cosmology and Astroparticle Physics 2014.09 (2014): 003.

[11] Meyer, Manuel, James Davies, and Julian Kuhlmann. "gammaALPs: An open-source python package for computing photon-axion-like-particle oscillations in astrophysical environments." arXiv preprint arXiv:2108.02061 (2021).

[12] M. Murgia, F. Govoni, L. Feretti, et al., Magnetic fields and Faraday rotation in clusters of galaxies, A&A 424 (2004) 429–446, [astro-ph/0406225].

[13] Peccei, Roberto D., and Helen R. Quinn. "Constraints imposed by CP conservation in the presence of pseudoparticles." Physical Review D 16.6 (1977)

[14] P. E. J. Nulsen and H. Bohringer, A ROSAT determination of the mass of the central Virgo Cluster, Mon. Not. Roy. Astron. Soc. 274 (June, 1995) 1093–1106.

[15] Raffelt, Georg, and Leo Stodolsky. "Mixing of the photon with low-mass particles." Physical Review D 37.5 (1988)

[16] H. R. Russell, A. C. Fabian, B. R. McNamara and A. E. Broderick, Inside the Bondi radius of M87, Mon. Not. Roy. Astron. Soc. 451 (July, 2015) 588–600, [1504.07633].

[17] Tully, R. Brent, Hélène M. Courtois, and Jenny G. Sorce. "COSMICFLOWS-3." The Astronomical Journal 152.2 (2016): 50.

PoS(Gamma2022)182

[18] O. Urban, N. Werner, A. Simionescu, S. W. Allen and H. Bohringer, X-ray Spectroscopy of the Virgo Cluster out to the Virial Radius, Mon. Not. Roy. Astron. Soc. 414 (2011) 2101, [1102.2430].

[19] Vacca, V., et al. "The intracluster magnetic field power spectrum in A2199." Astronomy & Astrophysics 540 (2012): A38.

[20] Weinberg, Steven. "A new light boson?." Physical Review Letters 40.4 (1978)

[21] Wilczek, Frank. "Problem of Strong P and T Invariance in the Presence of Instantons." Physical Review Letters 40.5 (1978)

[22] Wu, Dan-di. "A brief introduction to the strong CP problem." Zeitschrift für Naturforschung A 52.1-2 (1997): 179-182.

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