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Low-power pulsed emission at the spin period of the white dwarf in AR Scorpii?

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Previous high energy studies of AR Sco suggest that the surrounding region complicates the search for γ-ray emission from this close binary system. The fact that AR Sco lies close to the Galactic plane, Rho Oph cloud complex and strong nearby VHE *Fermi* sources, make it difficult to constrain and quantify an upper-limit of the emission from AR Sco's location in the sky. In this study, a search for high energy γ-ray emission was conducted to identify possible pulsed emission signatures within or above the noise level. Period analysis revealed low-level but consistent emission at the spin period of the white dwarf ($P_s = 117$ sec), using *Fermi*-LAT data from the past decade. Control analysis appears to show a decrease in signal strength at the spin period in regions further away from the coordinates centred on AR Sco, which may indicate the presence of low-level pulsed γ-ray emission from AR Sco.

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1. Introduction

AR Scorpii (henceforth AR Sco) is an enigmatic close binary system which is observable across most of the electromagnetic spectrum, [1]. The system consists of a $0.81 - 1.29 M_{\odot}$ highly magnetic white dwarf with a surface magnetic field B $\leq$ 500 MG [2, 3] orbiting a $0.28 - 0.45 M_{\odot}$ M5 spectral-type dwarf star with an orbital period of $P_{\rm orb}$ = 3.56 hours. Multi-wavelength emission consists of both thermal and non-thermal components, where non-thermal emission has been observed from radio to X-ray, [1, 3, 8]. This implies that AR Sco may be a source where particles are accelerated to relativistic energies, perhaps in the magnetosphere of the white dwarf with associated pulsed pulsar-like emission through, among other, synchrotron radiation.

An emphatic theoretical framework was provided by Buckley et al. (2017), [2], in an attempt to explain the multi-frequency emission from AR Sco from radio frequencies to X-ray energies. By doing optical observations utilizing the South African Astronomical Observatory (SAAO) HIPPO Polarimeter [4] on the 1.9 m telescope, strong levels of linear polarization (up to 40%) with significantly lower levels of circular polarization (< 10%) were revealed, [2, 3], which perhaps signifies a significant synchrotron component in the radio to X-ray part of the Spectral Energy Distribution (SED) of AR Sco. The morphology and pulse profile of the linear polarization are similar to that of the Crab pulsar, which is a young isolated neutron star pulsar that emits radiation from radio to TeV energies, e.g. [5]. The nature of the linear polarization profile is also consistent with synchrotron emission produced in the magnetic field of a rotating magnetic dipole, strengthening the notion that the white dwarf in AR Sco may in fact be a "white dwarf pulsar" which can produce non-thermal pulsar-like emission.

The apparent lack of accretion in the system also suggests that the highly magnetic white dwarf is primarily spin-powered, similar to pulsars, where particles can be accelerated to produce non-thermal emission. Marsh et al. (2016), [1] revealed that the white dwarf in the system is currently spinning about its own axis, at a period of $P_{\rm spin} = 117$ s, with strong supplementary pulsations at the beat period $P_b = 118$ s, which is the period between the spin and orbital period, [1]. It has been shown that it is possible for fast rotating magnetic white dwarfs to produce γ-ray emission through relativistic particle acceleration. The acceleration of particles in the magnetosphere of a rotating white dwarf is controlled by the electric field structure which is determined by the distribution of ionized gas around the star. Thus, if the white dwarf lacks a hot corona or is experiencing low/zero amounts of accretion, the surrounding area effectively acts as a vacuum. The absence of accretion in AR Sco and consequently a conducting plasma, allows for an estimated upper-limit in the electrical potential of the order

$$\Delta V \leq 10^{12} \left(\frac{P_{\rm wd}}{117 \text{ s}} \right)^{-5/2} \left(\frac{\mu}{8 \times 10^{34} \text{ G cm}^3} \right) \left(\frac{R_{\rm wd}}{5.5 \times 10^8 \text{ cm}} \right) \text{V} \tag{1.1}$$

to be induced between the white dwarf and the light cylinder, [2]. In the above equation $P_{\rm wd}$ and $R_{\rm wd}$ represent the spin period and radius of the white dwarf respectively, with the magnetic moment defined by μ. Since the electric field is several orders of magnitude stronger than the force

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of gravitation, charged particles such as electrons (and ions) can be pulled from the white dwarf's surface and accelerated to relativistic energies of the order of $\gamma_e \approx 10^6$, [2].

A theoretical model have also been presented by Geng et al. (2016) [6], who modelled the emission as being the result of the interaction between the highly magnetized white dwarf and the M5-type secondary dwarf star. In this model it is proposed that the white dwarf is a nearly perpendicular rotator where both magnetic poles sweep across the M-type star periodically. The interaction between the particle beam streaming out from the open field line regions and the M-type wind would lead to the formation of a 'bow shock', where the relativistic particles can be accelerated by e.g. magnetic pumping and shocks to produce possible synchrotron radiation from relativistic electrons in the magnetosphere of the secondary. However, other non-thermal theoretical models have also been developed postulating very high energy (VHE) γ-ray production through a hadronic channel like π^o, [7], as well as inverse-Compton (IC) scattering [3, 8]. It is also suggested that the relativistic electrons are trapped within the white dwarf's magnetic field lines due to the magnetic mirror effect, accelerating particle through a scattering process, [8]. The above mentioned models all serve as viable scenarios where particles can be accelerated to relativistic energies to produce the observed non-thermal emission from AR Sco. Hence, exploring the γ-ray regime of AR Sco makes it essential to constrain possible mechanisms for the observed non-thermal emission of AR Sco at higher energies.

2. *Fermi*-LAT Analysis

Previous high energy studies utilizing the *Fermi*-LAT telescope appears to show low level upper-limit detections between the energy range of 100 MeV and 500 GeV, [9]. By using a standard binned likelihood analysis, low level upper-limit emission at the $\leq 4.31\sigma$ significance level from the position of AR Sco, using a broken power-law model, was obtained. It is speculated that AR Sco's surrounding region may influence the upper-limit emission at high energies. The fact that the system lies close to the Galactic plane, the Rho Oph cloud complex and nearby high energy sources, along with *Fermi*-LAT's low spatial resolution at lower energies (0.6° at $\leq$ 1 GeV), [10], makes it difficult to constrain the upper-limit values. Considering these results, a search for emission at noise level was conducted by means of period analysis.

By doing a period analysis, a search for uniformity of a phase distribution at a certain predetermined period was investigated. Since the spin ($P_{spin} = 117$ s) for the rapidly rotating white dwarf is known and detectable from radio to X-ray, (e.g. [1, 2, 8]), accompanied by the argument that the white dwarf in AR Sco has similar features to that of spun-up pulsars, (e.g. [2, 3]), a search for any periodicities around this period was considered. By using Pass 8 Release 3 (P8R3) *Fermi*-LAT data from the past decade (4 August 2008- 18 March 2019)[1] a standard periodic analysis was performed in an attempt to search for pulsed emission above the *Fermi*-LAT threshold. `SOURCE` class event files within a Region of Interest (ROI) of 10° centred at AR Sco (RA:$16^h21^m47.28^s$, Dec: $-22°53'10.39''$, J2000), were considered during analysis. Due to the fact that most of the

[1] Extracted from the Fermi Science Support Center (FSSC) [11]

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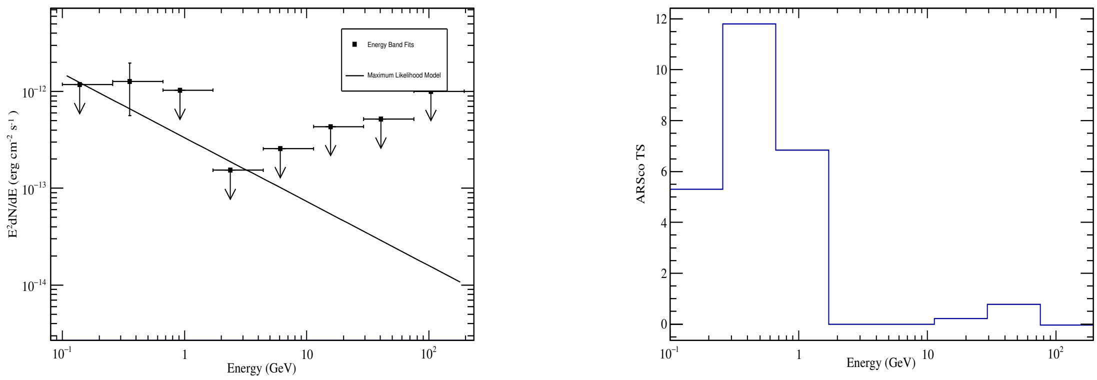
observed emission lies below 3 GeV (see Fig. 1) an energy range of 100 MeV - 30 GeV was chosen, including the latest spacecraft file at the time of analysis, and used to obtain power spectra (periodograms) with the help of the `gtpsearch` tool.



(a) Energy flux SED obtained using `bdlikeSED`.

(b) TS values vs energy of γ-ray photons.

Figure 1: AR Sco SED using the power-law model over 9 energy bins (a) shows 2σ upper-limit energy flux values (with a 3σ data point) based on a limiting TS ≤ 9 value per bin due to the low overall significance of AR Sco. The distribution of TS values per energy bin (b) also illustrates that the most significant emission is concentrated in the energy bins below 3 GeV. Distribution of high energy γ-rays are more likely to be detected at lower energies. Adopted from Kaplan et. al (2019), [9].

3. Results and Discussion

Rayleigh periodograms for AR Sco were produced by using the ephemeris from Takata et. al (2018) [8], with a reference time of $T_{s,ref} = 57641.546$ MJD and the spin frequency $\nu_{\rm spin} = 8.5390$ mHz (117.1 s). The spin-down frequency of the white dwarf in AR Sco's ($\dot{\nu} = -2.86 \pm 0.36 \times 10^{-17}$ Hz s^{-1}), was adopted from Marsh et. al (2016) [1]. A Rayleigh power spectrum centred on the coordinates of AR Sco, folded on the spin frequency of the white dwarf is shown in Fig. 2. Considering the long baseline of events in the dataset, a step size of 2.985×10^{-6} Hz at a Fourier resolution of ($\nu = 2.985 \times 10^{-9}$ Hz) was used with a number of trials as 5000, centred on the fundamental frequency of $\nu_{\rm spin} = 8.53885$ mHz $(117.11$ s$)$.

A narrower Rayleigh power spectrum (Fig. 3) with step size (1.493×10^{-9} Hz) of 0.5 times the Fourier resolution of ($\nu = 2.985 \times 10^{-9}$ Hz) and number of trials 500, centred on the fundamental frequency of $\nu_{\rm spin} = 8.53885$ mHz $(117.11$ s$)$ was obtained, covering frequencies from $8.5384 - 8.5393$ mHz. From this Rayleigh power an apparent signal at the fundamental spin frequency seems to be visible, albeit not at a significant level. By focusing on this fundamental frequency ($\nu_{\rm spin} = 8.53885$ mHz), we can see a more defined power spectrum, with step size (2.895×10^{-10} Hz) of 0.1 times the Fourier resolution of ($\nu = 2.985 \times 10^{-9}$ Hz) and number of trials 500.

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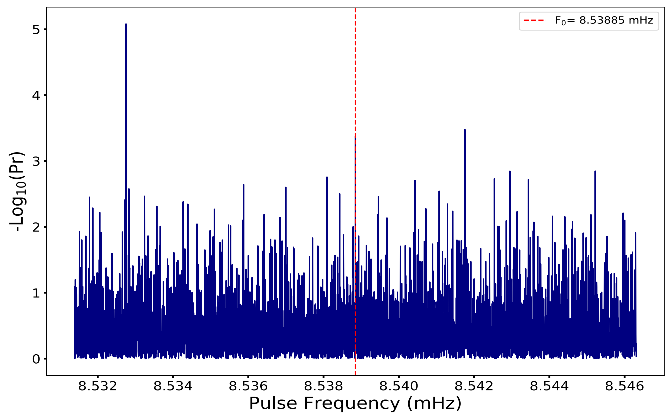

Figure 2: Rayleigh periodogram of AR Sco in the energy range of 100 MeV to 30 GeV, focusing on the spin period frequency range, covering frequencies from 8.530 – 8.547 mHz. Additional line marker added showing the fundamental spin frequency ($F_0 = 8.53885$ mHz) of the white dwarf in AR Sco.

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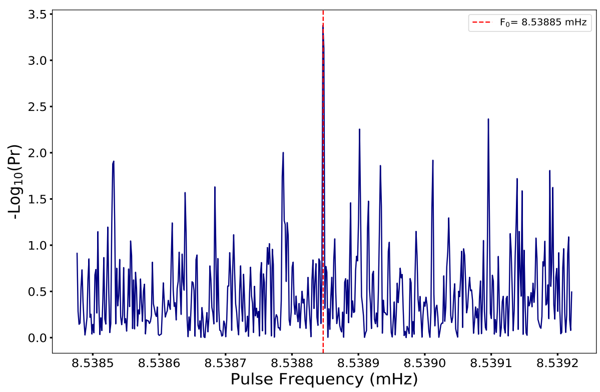

Figure 3: Rayleigh periodogram of AR Sco in the energy range of 100 MeV to 30 GeV, covering frequencies from 8.5384 – 8.5393 mHz.

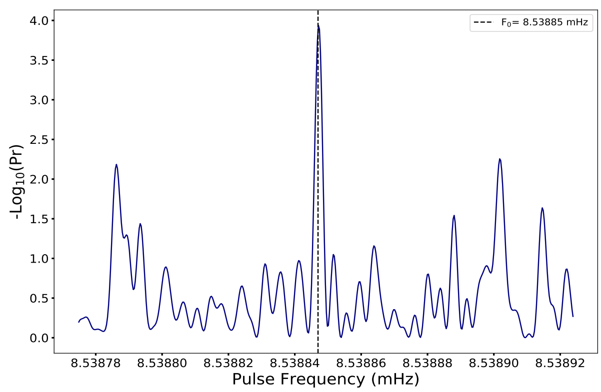

Figure 4: Rayleigh periodogram of AR Sco in the energy range of 100 MeV to 30 GeV, focusing on the spin frequency range (8.53877 – 8.53893 mHz).

3.1 Periodicity control test

To determine the validity of the power spectra, a search for a similar signal within the extracted *Fermi*-LAT dataset at locations further away from the position centred on AR Sco (within the ROI), where no γ-ray sources are detected and the γ-ray background is at a significantly low level (see Fig. 5), was conducted. If a signal is detected at any of these independent locations at the same spin frequency with the same properties as AR Sco, then the proposed signal detected in the power spectra from AR Sco could possibly be inherent to the analysis technique or data set. However, if the data reveals white noise structures, with no clear signals at locations without any suspected γ-ray sources, it will strengthen the case that the analysis technique and results obtained are justifiable. The locations were chosen to be 2°, 3°, 5° and 8° away from the ROI centre, where low-level or no γ-ray emission is present (see Fig. 5). Rayleigh periodograms compared to each region within the ROI (centred on AR Sco) are presented in Fig. 6 and Fig. 7.

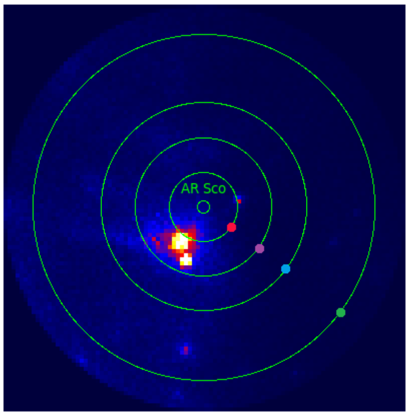

Figure 5: Counts map (100 x 100 pixels) centred on AR Sco. Green circles represents locations 2° (red), 3° (violet), 5° (blue) and 8° (green) away from the coordinates centred on AR Sco.

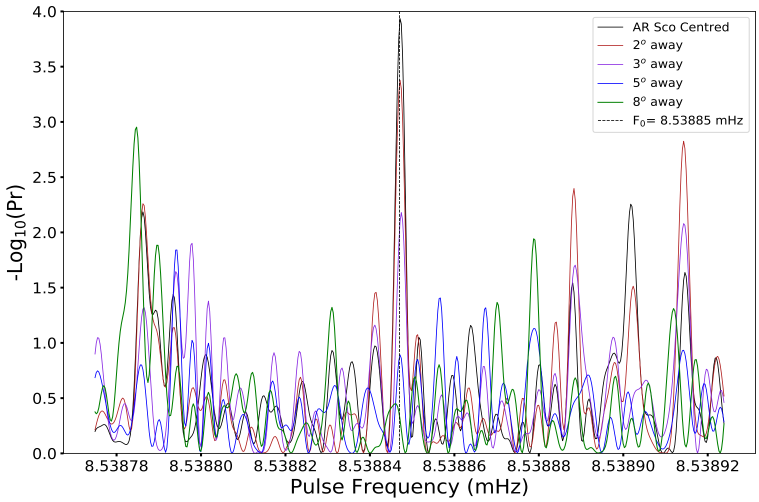

Figure 6: AR Sco power spectra (black) compared to regions 2° (red), 3° (violet), 5° (blue) and 8° (green) away from the coordinates centred on AR Sco.

4. Conclusion

From the results obtained in Fig. 4, there appears to be evidence of a power peak centred at the current ephemeris model frequency for the spin period $\nu_{\rm spin} = 8.53885$ mHz $(117.11$ s$)$. Compared to the model frequency obtained by Takata et. al (2018) [8], $\nu_{\rm spin} = 8.5390$ mHz $(117.1$ s$)$, the periodogram frequency of our current analysis is much narrower and focused on a more precise value for the white dwarf's spin frequency. This value is well within the power peaks from the periodograms obtained by Takata et. al (2018) [8].

Validity tests performed also appears to suggest a possible low-level pulsation at the spin frequency. Compared to regions further away from the ROI centre (see Fig. 6), where no known γ-ray emission is visible and only background noise is considered, it appears that the Rayleigh power at the fundamental spin frequency is decreasing in strength as one moves further away from the position centred on the coordinates of AR Sco. Even though the validity test appears to show

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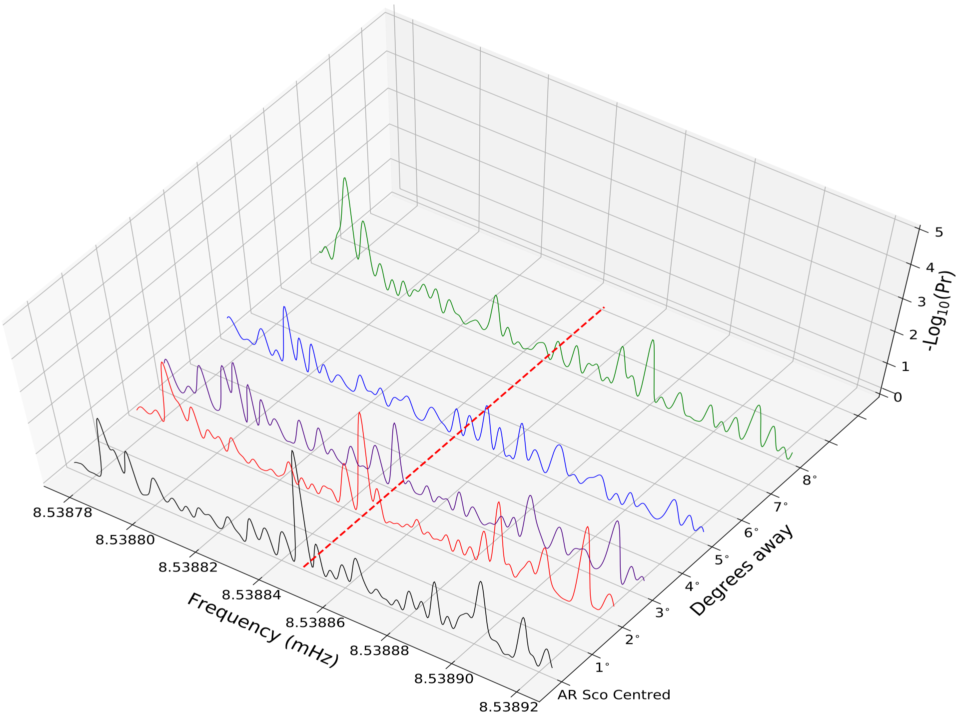

Figure 7: AR Sco power spectra (black) compared to regions 2° (red), 3° (violet), 5° (blue) and 8° (green) away from the coordinates centred on AR Sco.

a possible signal within the noise structure, confirmation of this signal can only be considered through further examination and studies. Since pulsed emission has been detected at the beat period of the white dwarf over most of the electromagnetic spectrum, [1, 2, 8], future prospects is aimed towards similar high energy period analysis for the beat period. Alternatively, period analysis of an independent source(s), using the same ephemeris of AR Sco, can be performed to serve as a second control test to confirm the validity of the technique used and results obtained for the spin period of the white dwarf.

It has been shown that AR Sco's SED can not be described by synchrotron emission alone, [12], and more comprehensive studies need to be conducted. In terms of energy, it has been shown that relativistic electrons with energies of $\gamma \sim 10^6 - 10^7$ can provide the possibility for the production of high energy γ-rays by up-scattering of soft photons from the companion star through the IC process, [13]. This is similar to the scenario proposed in nova-like variable star AE Aqr, [14]. An upper-limit for the γ-ray energies produced from these electrons is estimated to be ~ 1 TeV. The IC process in the outer gap model has also been explored by Takata et al. (2017), [15], which can produce photons with energies of > 0.1 TeV. Bednarek (2018), [7], has shown that it is possible to reach GeV-TeV energies through a hadronic model. The possibility therefore exists that high energy emission can be detected and better constrained with the increased sensitivity of CTA (Cherenkov Telescope Array). Compared to *Fermi*-LAT, CTA offers a larger collection area

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and better angular resolution, which make observations of faint γ-ray sources much more efficient, [16]. Overlapping regions of energy between these two observatories also show that at an energy of about 40 GeV, *Fermi* will be doing measurements within a 10 year period that is comparable in quality to measurements of 100 hour observations with CTA, see Fig. 8. Hence, future studies using the CTA system could therefore increase the probability for detection of low-level pulsed high energy or VHE emission from AR Sco and constrain the origin and parameters of the possible high energy emission to determine the exact energy production mechanism.

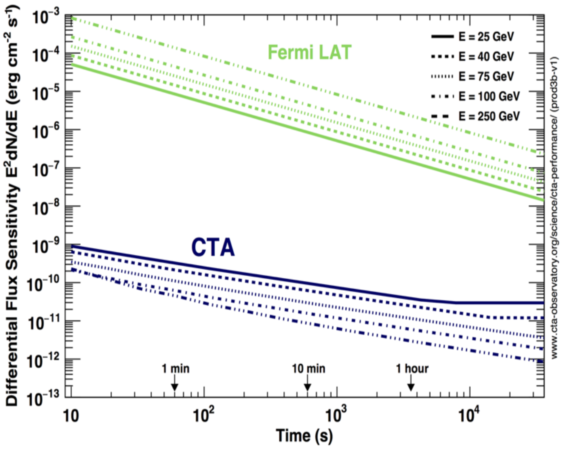

Figure 8: Differential sensitivity at selected energies as a function of observation time for CTA and *Fermi*-LAT. Adopted from CTA Consortium (2019), [17].

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