Search for Gamma-ray emission in the White Dwarf pulsar of AR Scorpii

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Abstract. Detailed multi-frequency studies of the white dwarf pulsar AR Scorpii (AR Sco) revealed a Spectral Energy Distribution (SED) which predominantly shows features of non-thermal emission between the Radio and X-ray energies. This implies that AR Sco is a site of particle acceleration, which makes AR Sco an interesting source to investigate for possible gamma-ray emission in Fermi-LAT data (100 MeV-500 GeV). The focus of this paper was to do a preliminary analysis of the total Fermi-LAT dataset (2008-2018) by utilizing the upgraded Fermi-LAT Pass 8 data analysis pipeline to search for possible γ-ray emission in AR Sco. The detection of gamma-rays from AR Sco will be a strong motivation for possible CTA and H.E.S.S. follow-up studies. A positive detection will also be invaluable to the field of gamma-ray astronomy, establishing close binaries containing fast rotating, highly magnetic white dwarfs as a new class of γ-ray source.

1. Introduction

AR Scorpii (henceforth AR Sco) is a newly discovered close binary system consisting of a highly magnetic white dwarf pulsar and a M5 spectral type red dwarf orbiting around their Center of Mass (COM) every 3.56 h[1]. This suggest some relation to other close binary systems called Cataclysmic Variables (CV) stars. A certain subclass of CVs known as Intermediate Polars (IP), also consist of white dwarfs with strong magnetic fields ranging between 1-10 MG, which is similar to that of AR Sco. White dwarfs (WDs) are very dense stars in their final evolutionary state, supported by electron degeneracy pressure. Some of these WDs spin rapidly about their central axis, possibly due to mass transfer from their companion star. They thus mimic the properties of neutron star pulsars due to their fast rotational velocities and large magnetic fields[2]. Recently it was discovered that the rotating WD in AR Sco, with a spin period of $P_s = 117$ s, shows strong brightness variations across most of the electromagnetic spectrum[1], i.e. the emission predominantly modulated at the orbital ($P_o = 3.56$ h) and its beat period ($P_b = 118$ s) with spin period $P_s = 117$ s.

It has been shown that this close binary system is unique, since there is no evidence of mass transfer, mass accretion, or magnetospheric propelling of the mass transfer stream from the binary system[4]. It was suggested by Marsh et al.[1] that AR Sco is in the evolutionary stage of an IP, but AR Sco's optical pulsations (70%) far exceeds that of the brightest IP detected thus far, namely FO Aquarii with optical pulsations of 25%. The lack of substantial accretion is inferred from the fact that the X-ray luminosity of AR Sco is less than 1% that of a typical IP[1]. Therefore, there is no clear evidence to support the notion that AR Sco is an IP.

It was also suggested by Buckley et al.[4] that the Spectral Energy Distribution (SED) is dominated by non-thermal emission[4]. One of the most dominant emission features occurs in the radio regime, where strong modulations were found in the radio flux on the orbital period and the beat period[3] suggesting the emission originates on the M5 secondary star. Possibly in the pumped magnetospheric field of the secondary star as the WD's magnetic field sweeps across it every rotation cycle. It is also proposed that the highly magnetic WD pulsar (order of 10 MG) has the potential to accelerate charged particles like electrons and protons to high Lorentz factors ($\gamma \approx 10^6$) within the light cylinder of the rotating white dwarf[4]. This provides a vehicle to produce gamma-rays with energies above 1 TeV through e.g. inverse Compton scattering between the relativistic electrons and the photons from the secondary star[2]. However, it was also recently shown that very high energy gamma-ray production through a hadronic channel like π°-decay is also possible[5].

The aim of the study presented in this paper is to do a complete analysis of the total Fermi-LAT dataset (2008-2018) utilizing the upgraded Fermi-LAT Pass 8 data analysis pipeline to search for a gamma-ray excess from AR Sco. By using the upgraded Pass 8 data pipeline, better constraints can be put on the level of the emission above 100 MeV, which will allow the determination of a high energy SED above this threshold[6]. This will have important implications for follow-up studies with H.E.S.S. and the future CTA. This study will have a very significant impact in the field of multi-wavelength astrophysics of high energy compact sources, as well as the field of gamma-ray astronomy. The discovery of gamma-rays in AR Sco will lead to a new class of gamma-ray source and the multi-wavelength properties will result in the source being considered as a unique laboratory to study magnetospheric processes that can accelerate charged particles to very high energies.

2. Observations and Analyses

A Fermi-LAT dataset from the past decade (2008-2018) was extracted from the Fermi Science Support Center (FSSC) in the energy range between 100 MeV and 500 GeV. By using the Pass 8 data analysis pipeline, which provides a better determination of the diffuse galactic gamma-ray emission and also a significant improvement in terms of energy resolution from previous Fermi-LAT pipelines, it was possible to do a standard Binned Likelihood Analysis on the Fermi-LAT dataset[7]. The analysis was performed using Fermipy packages where a number of models were experimented with to fit and produce high energy SEDs for AR Sco. The event files, i.e. the photon and spacecraft files that were extracted from the FSSC site, were chosen to have a Region of Interest (ROI) of 30°, while a 15° ROI was chosen to extract the high energy photons of the target for analysis. All the point sources in the third Fermi-LAT catalog (3FGL) located within the ROI were modelled in the spectral fits, including the isotropic background and galactic diffuse emission. Since AR Sco is not listed in the 3FGL catalog, the source (3FGL J1616.8-2300) closest to the ROI centre (0.01° from ROI centre) was chosen to perform the event selection and create the source maps with Fermipy. AR Sco was added using its coordinates, (RA:$16^h21^m47.28^s$, Dec: $-22°53'10.39''$, J2000) to the source maps and selection files with the help of Fermipy commands so that likelihood analysis could be done. The spectral shape parameters of AR Sco was set to vary during optimization and fitting. The spectral shapes used to model the spectral fit for the extracted data are as follows, namely 1.) a Power Law:

$$dN(E)/dE = N_0(E/E_0)^{\Gamma}, \tag{1}$$

with N_0 is the normalization factor and where a pivot energy (E_0) of 1 GeV was chosen to fit the model, and 2.) a Log Parabola

$$dN(E)/dE = N_0(E/E_b)^{\alpha-\beta log(E/E_b)}, \tag{2}$$

where E_b is the break value that should be set near the lower energy range of the spectrum. Here E_b was chosen to be 1 GeV.

Table 1. List of all the model parameters used during optimization to fit the Fermi-LAT data. Where the Test Statistic (TS) value is used to distinguish between flux values (TS $\geq$ 25) and 2σ upper limits.

Spectral model	TS	α	β	Γ
Power Law	7.71	N/A	N/A	2.44 $\pm$ 0.05
Log Parabola	16.17	2.29 $\pm$ 0.2	0.28 $\pm$ 0.001	N/A

3. Results and Discussion

The spectral models that were used to model the SED, as mentioned in Section 2, are the power law and log parabola functions. These models were used to determine the emission spectrum that best describes the emission properties from AR Sco. A residual model fit, see Figure 1, was also created to visually indicate how well the model has been fitted to the high energy data.

The upper limits and detected flux values were determined by using the Test Statistic (TS) values generated by the likelihood analysis. These TS values help to determine the probabillity of detecting emission from the source within each bin. Based on the parameters and overall test statistics (see Table 1) and taking in account how both the power law and log parabola fits the flux values and upper limit within the butterfly plot, see Figure 2 and 3, the best proposed significant fit for AR Sco is represented by the power law model, see Figure 2. Also, from the residual and counts fit (Figure 1), along with the produced SEDs (Figures 2 and 3), it is observed that the most of these detected flux values are within the lower energy regime (up intill $\sim$10 GeV). TS maps were also generated to show the overall significance of detection from AR Sco within the ROI, see Figure 4 and 5. The bright spot in the ROI, centred at AR Sco, in Figure 6 suggests that there is possible high energy emission from this region. Histograms of significance of all the data points in the ROI also shows the probability of detection within the standard deviation, see Figure 6 and 7. From these figures it is clear that the probability of detection is higher for the power law model as it follows a better Gaussian curve than the log parabola model.

A broadband SED was also created to show how the obtained Fermi-LAT power law spectrum, ranging from 100MeV to 500GeV, can be viewed in relation to previous multi-frequency observations (see Figure 8). The radio to optical data were extracted from the paper published by Marsh et al.[1] in 2016, whereas the X-ray data was extracted from the paper published by Geng et al.[3] in 2016.

4. Conclusion

The gamma-ray SED between 100MeV-500GeV seems to be compatible with a power law with Γ=2.4 $\pm$ 0.05. Our results seem to suggest the possibility of a low-level detection which is compatible with both hadronic and leptonic channels of gamma-ray production. Further analyses are underway to quantify the gamma-ray emission from the selected ROI centred on AR Sco. Unbinned likelihood analyses will also be performed, utilizing all the detected high energy photons, to better determine the gamma-ray excess.

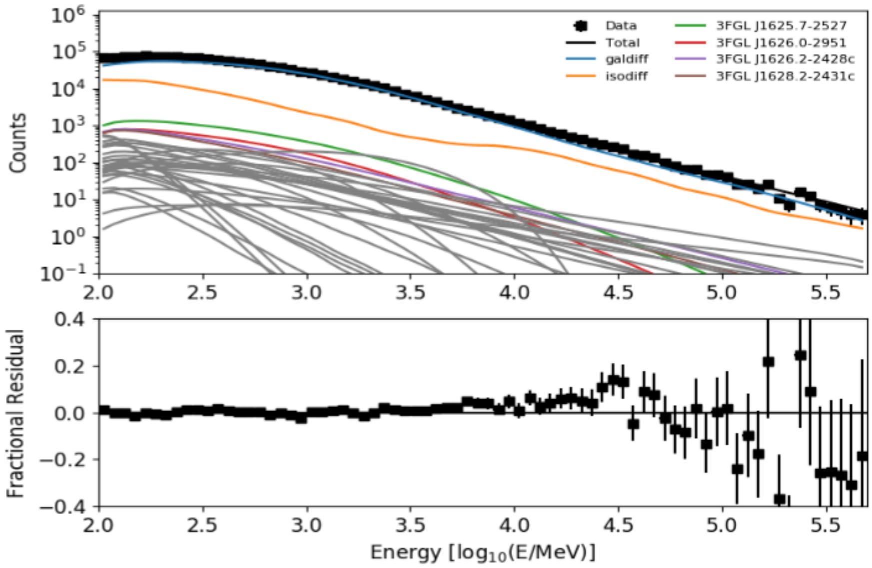

Figure 1. Residual model fit of power law model which best describes the spectral energy distribution.

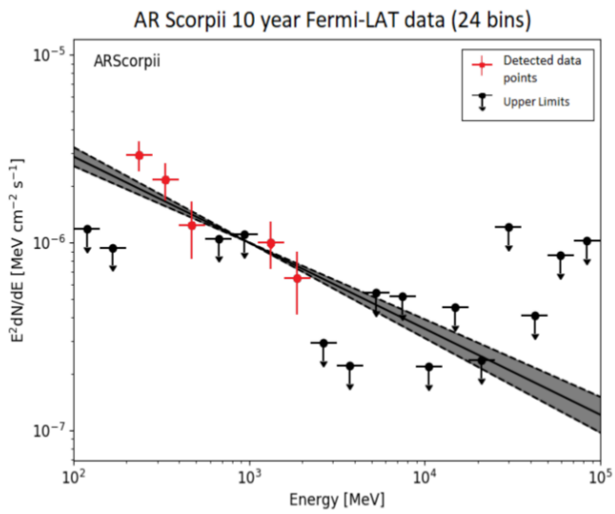

Figure 2. Spectral energy model fit of AR Sco's high energy SED represented by the Power Law function.

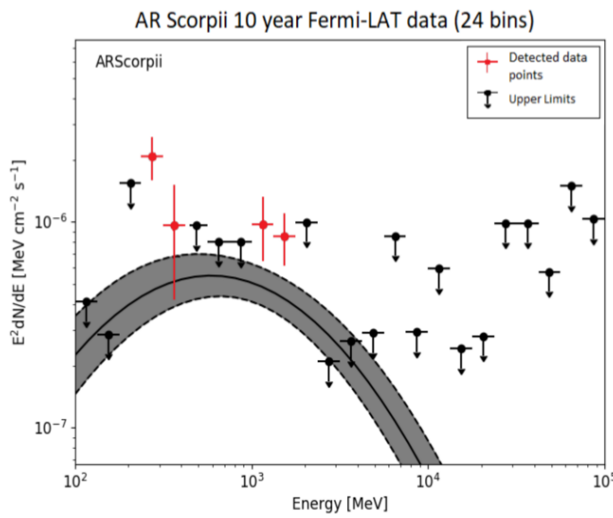

Figure 3. Spectral energy model fit of AR Sco's high energy SED represented by the Log Parabola function.

 ISBN: 978-0-620-85406-1

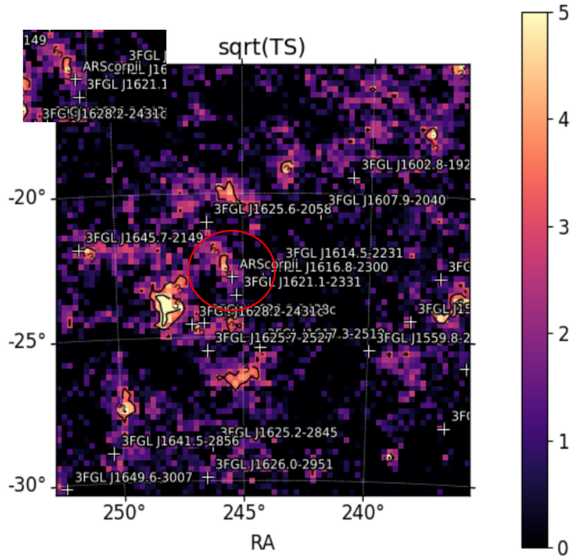

Figure 4. Test Statistic map of the source AR Sco and the galactic diffuse emission. Notice the bright pixels at the ROI centre (red circle).

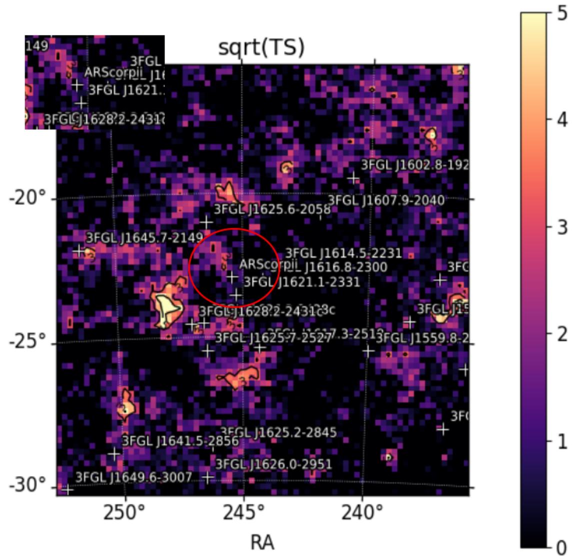

Figure 5. Test Statistic map of just the galactic diffuse emission. Notice the lack of bright pixels at the ROI centre compared to that in Figure 6.

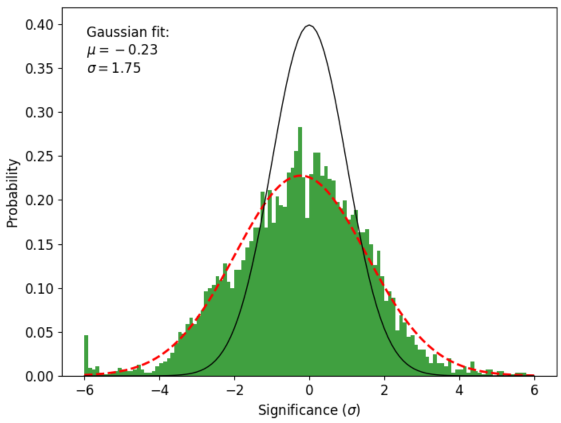

Figure 6. Histogram of significance for all the points on the map, Power Law model.

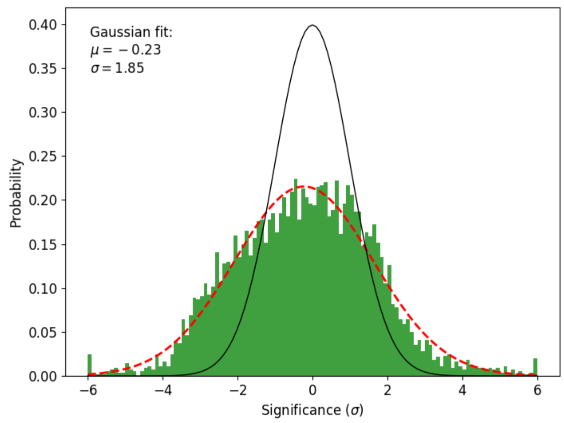

Figure 7. Histogram of significance for all the points on the map, Log Parabola model.

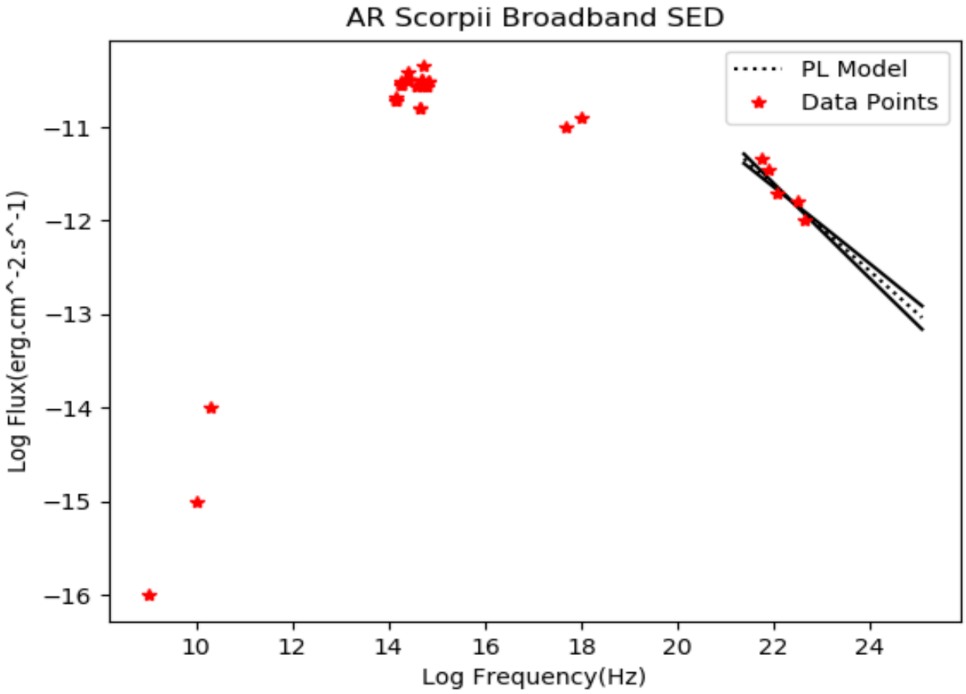

Figure 8. Proposed Broadband SED of AR Sco, ranging from radio to gamma-ray energies. Radio and optical data adapted from Marsh et al.[1] and Geng et al.[2]. The dashed and solid lines show the Power Law model butterfly plot produced by the Likelihood Analyses generated in Fermipy.

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