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Exploring the nature of AE Aquarii at higher energies using Sazuku and Fermi-LAT

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The nova-like variable AE Aquarii is a unique system that shows emission at almost all wavelengths. The emission in radio, optical and soft X-ray has been explored extensively, whereas the nature of the emission towards higher energies such as hard X-ray and gamma-ray wavelengths is still not clearly defined.

In this study a search for pulsed emission has been conducted utilizing *Suzaku* and *Fermi*-LAT data. The methodology and results from the analysis will be shown. The results from the analysis show that the possibility of a non-thermal component towards higher energies in AE Aquarii cannot be excluded.

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1. Introduction

AE Aqaurii is a unique nova-like magnetic cataclysmic variable star system. It consists of a fast rotating white dwarf (WD) primary star that is in the ejector state with a propeller mechanism driving the in-falling matter from the secondary star away in the form of interacting blobs [1]. The secondary is a K2-K5 type evolved star, with the primary and secondary components orbiting the centre of mass of the system at a $P_{orb} = 9.88$ h [2, 3]. The highly magnetized WD ($B_1 \sim 10^6$G) [4], which has a spin period of $P_{spin} \approx 33$ s, is spinning down at a rate of $\dot{P}_{spin} = 5.64 \times 10^{-14}$ s s^{-1}, resulting in a spin-down luminosity of $-I\dot{\Omega}\Omega = 6 \times 10^{33} I_{50}$erg s^{-1} [5], where $I_{50} = \frac{I}{10^{50}\text{g cm}^{-2}}$. The spin-down luminosity $-I\dot{\Omega}\Omega$ was determined from the white dwarf moment of inertia $I \approx 0.2\ M_{WD}R_{WD}^2 \approx 2 \times 10^{50}$ g cm^2 with M_{WD} the WD mass and R_{WD} the WD radius, with the 0.2 factor extrapolated from [6] for a WD mass of $\sim 0.48\ M_\odot$ [7], in addition with $\Omega = 2\pi/P_{33} = 0.19$ s^{-1} and $\dot{\Omega} = -2\pi\dot{P}/P^2 = -3.24 \times 10^{-16}$ s^{-2}. This large spin down power is ~ 120 times greater than the inferred accretion luminosities derived from UV [8] and X-ray emission [9], and could act as a reservoir that drives non-thermal particle acceleration [10], explaining the radio synchrotron and possible high energy (γ-ray) emission.

The system has been extensively studied, and the emission mechanisms for the radio, optical and soft X-ray components are well and clearly defined in terms of the currently proposed models. In spite of a number of studies into the nature of possible emission towards higher energies, such as hard X-ray and γ-ray, there is still substantial uncertainty as to whether AE Aquarii is an emitter of pulsed radiation at energies above $\varepsilon_\gamma \sim 10$ keV.

The X-ray emission has been studied since the discovery of the WD spin pulsations in *Einstein* data [11]. Subsequent studies utilised data from *ASCA, XMM-Newton, Chandra, Swift* and *Suzaku* to detect, define and model the soft and hard X-ray emission components. The soft X-ray emission ($\leq$ 10keV) component has been fitted with a multi-thermal model [12, 13], with the very strong 33 s pulsations used to update the WD spin ephemeris [14]. The properties of the hard X-ray emission ($\geq$ 10keV), such as sharp pulse profiles, could best be described through non-thermal emission from accelerated particles, as proposed from a fit of a power-law model [12]. Correlations between the pulsations in the soft X-ray emission and the lower hard X-ray emission (10-25 keV) *Suzaku* data were also found [12]. The fitted multi-thermal components at temperatures of $2.9^{+0.20}_{-0.16}$ keV and $0.53^{+0.13}_{-0.14}$ keV as well as the excess above the extrapolated hard X-ray emission data, that was explained by either a third thermal component of $54^{+0.26}_{-0.47}$ keV or a power law with a photon index of $1.12^{+0.63}_{-0.62}$ for the 2005 and 2006 *Suzaku* data [12] can be seen in Figure 1.

The first observational studies conducted at Very High Energies (VHE) [$\varepsilon_\gamma \geqslant 0.1$ TeV] suggested possible optical-like VHE gamma-ray pulsed emission [15, 16, 17]. A study to search for TeV emission using the Whipple 10 m telescope found no evidence for any steady, pulsed or episodic emission [18]. The MAGIC telescope was utilised during follow-up studies, but again no evidence of any steady TeV gamma-ray emission was found [19]. In 2012 a multi-wavelength campaign using optical, UV, X-ray (*Swift*) and gamma-ray (MAGIC) telescopes was conducted [20, 21]. No significant detections for steady TeV as well as variable (33.08 and 16.54 s pulsed)

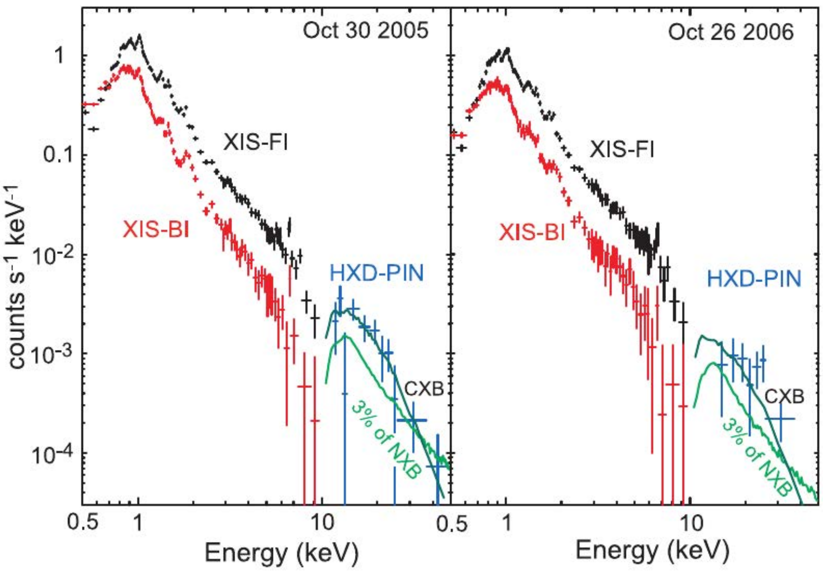

Figure 1: Background subtracted X-ray spectra of AE Aquarii from *Suzaku* data from 2005 (left) and 2006 (right). Indicated are the soft thermal emission spectra for the XIS front illuminated (black) and back illuminated (red) instruments, as well as the HXD PIN spectra (blue). The light and dark green curves indicates the PIN non X-ray background and the expected cosmic X-ray background respectively. Adopted from [12].

TeV emission were found. Upper-limit values of 6.39×10^{-12} cm^{-2}s^{-1} above 250 GeV and 7.401×10^{-13} cm^{-2}s^{-1} above 1 TeV for a power-law spectrum with a slope of -2.6 resulted from the campaign [20, 21]. Fortunately the advent of space-based telescopes such as *Fermi* and *AGILE* increased the amount of data available to utilise in the search for steady, pulsed or episodic γ-ray emission from this enigmatic source.

This study utilised data from *Suzaku* and *Fermi*-LAT in the search for and characterisation of non-thermal emission in AE Aquarii at higher energies. It is a continuation of the study presented in [22].

2. *Suzaku* XIS and HXD data analysis

The *Suzaku* Space Telescope was launched on 10 July 2005 into a low earth orbit (LEO) at 550 km altitude. It has two primary instruments, the soft X-ray instrument (XIS) that is sensitive between 0.2-12 keV and the hard X-ray detector (HXD) that is sensitive between energies of 10-600 keV. Additional information on the telescope and mission is available at `http://heasarc.gsfc.nasa.gov/docs/suzaku/`.

Suzaku observed AE Aquarii on three separate occasions during October of 2005, 2006 and 2009. As the 2005 and 2006 datasets were already previously analysed and discussed [12], only the 2009 dataset (ID 404001010), which had an on-source observation length of 294159 s, was used for this study. Spectral analysis of the XIS data as well as the HXD PIN data were performed using "XSELECT" (Version 2.4c) and "XSpec" (Version 12.8.2) available in the Heasoft (Version 6.15.1) software package available from the HEASARC site at `http://heasarc.gsfc.nasa.gov/`.

For the soft X-ray emission the cleaned xis0 and xis3 (front illuminated (FI) sensors), as well as the xis1 (back illuminated (BI) sensor) data were used. The source as well as sky background spectra were extracted and saved along with the latest calibration database (CALDB) response and model files. The xis0 and xis3 data were combined for a total FI spectrum. The selection of spectral models was based upon the previously mentioned studies. Multi-thermal Mekal models was first tested. An initial null model 2 component Mekal model was tested, but did not show a good fit below 1.5 keV as can be seen in Figure 2.

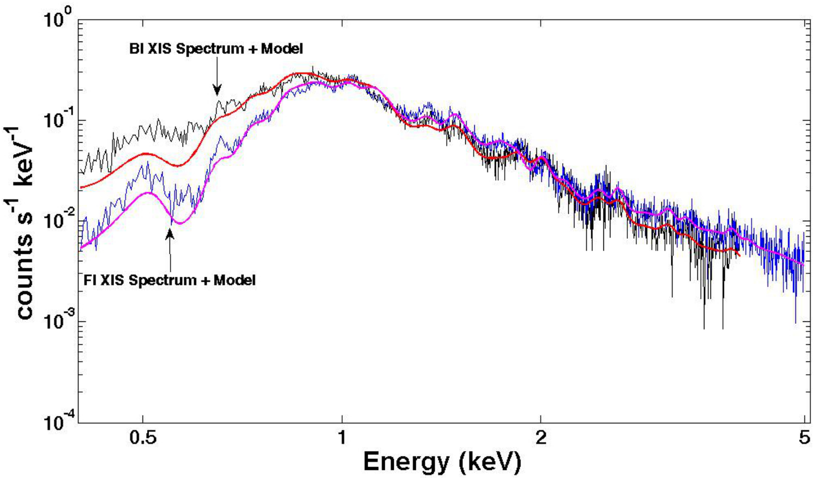

Figure 2: *Suzaku* XIS spectra for the FI (blue) and BI (black) data with proposed 2-Mekal models for the FI and BI spectra represented by the pink and red curves receptively.

An additional Mekal component was therefore added. It resulted in a fit to the FI data with a p-value of 2.678×10^{-22} with a reduced χ^2 value of 1.519, and a fit to the BI data with a p-value of 3.214×10^{-16} with a reduced χ^2 value of 1.466. An F-test comparison between the new proposed model and the null model resulted in F-statistic of 73.606 and p-value of 2.261×10^{-30} for the FI data and F-statistic of 130.454 and p-value of 1.337×10^{-49} for the BI data. However, the proposed model again showed an unacceptable fit below 1.5 keV as can be seen in Figure 3.

An additional Bremsstrahlung component was tested and subsequently improved the fit to the FI data with a p-value of 3.171×10^{-7} with a reduced χ^2 value of 1.25, and a fit to the BI data with a p-value of 4.24×10^{-6} with a reduced χ^2 value of 1.242. A F-test comparison between the new proposed model and the null model (2-Mekal) resulted in F-statistic of 93.804 and p-value of 7.06×10^{-67} for the FI data and F-statistic of 111.796 and p-value of 1.337×10^{-75} for the BI data. An F-test between the new proposed model and the 3-Mekal model (null model for this test) resulted in a F-statistic of 98.373 and p-value of 2.008×10^{-39} for the FI data and F-statistic of 70.043

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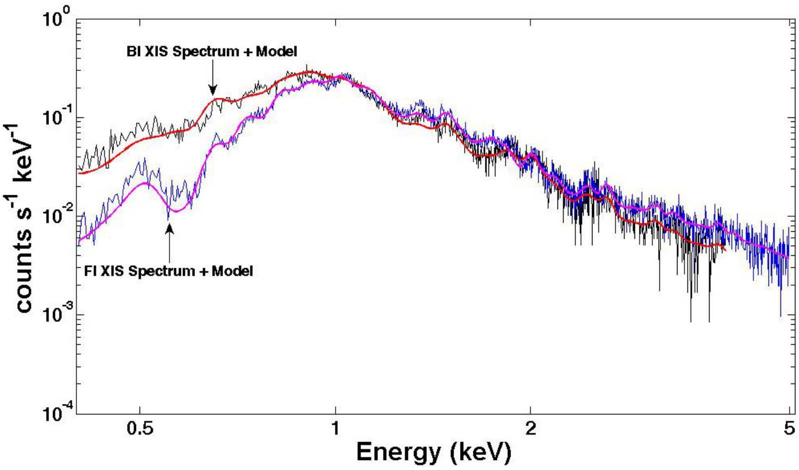

Figure 3: *Suzaku* XIS spectra for the FI (blue) and BI (black) data with proposed 3-Mekal models for the FI and BI spectra represented by the pink and red curves receptively.

and p-value of 1.071×10^{-28} for the BI data. The final accepted Multi-Mekal + Bremmsstrahlung model fitted spectra can be seen in Figure 4. The fitted model was then used to determine a flux value for the XIS data between energies of 0.4-5.0 keV of 8×10^{-12}erg cm^{-2}s^{-1}.

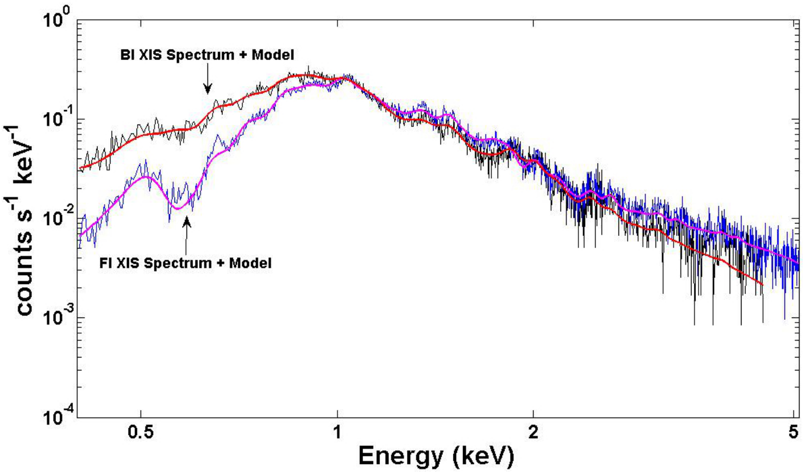

Figure 4: *Suzaku* XIS spectra for the FI (blue) and BI (black) data with proposed mutli-Mekal + Bremsstrahlung models for the FI and BI spectra represented by the pink and red curves receptively.

For the hard X-ray emission the RAW uncleaned PIN data was chosen, to make use of the ever improving instrument response and galactic background model files available from the CALDB. For the fit of the final extracted PIN spectrum, a simple power law was chosen. The fit resulted in a p-value of 2.2×10^{-6} with a reduced χ^2 value of 1.58. The fitted model was then used to determine flux values for the PIN data between energies of 14-40 keV of 1.6×10^{-11}erg cm^{-2}s^{-1} and 40-96 keV of 2.1×10^{-11}erg cm^{-2}s^{-1}. The PIN spectrum and fitted model can be seen in Figure 5. The model determined flux values for the soft X-ray emission (XIS) and hard X-ray emission (PIN) spectra were then also included in an updated spectral energy distribution (SED) diagram for AE Aquarii, Figure 10.

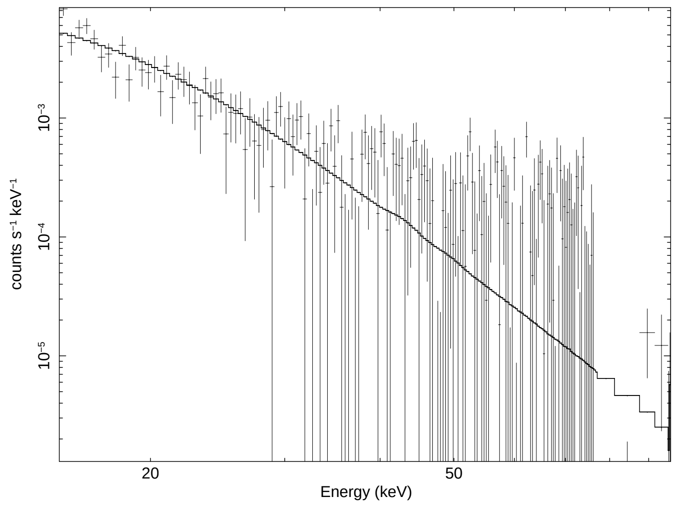

Figure 5: *Suzaku* HXD-PIN spectrum with proposed power-law model represented by the black curve. The error bars are statistical in nature.

3. *Fermi*-LAT data analysis

The Fermi Gamma-ray Space Telescope was launched on 11 June 2008 into a LEO at 550 km. The primary instrument is the Large Area Telescope (LAT) that is sensitive to energies between 20 MeV - 300 GeV. The telescope is predominantly in survey mode and covers the whole gamma-ray emission sky every 3 hours. Additional information on the telescope and mission is available from [23], Fermi ASI (Agenzia Speziala Italiana) Science Data Center (`http://fermi.asdc.asi.it/`) and the Fermi Science Support Center at HEASARC (`http://fermi.gsfc.nasa.gov/ssc/`).

Since the previous analysis of *Fermi*-LAT data as mentioned in [22] a more in depth analysis was performed on the available data sets, as well as more thorough testing of the relevant procedures used and results obtained. The selected data included Pass 7 datasets for energies between 100 MeV and 300 GeV, as well as subsets of the data in terms of different energy bins, for the time frame 239557417 - END (MET). Analysis was performed using Fermi Science Tools v9r32p5 in conjunction with the python LATAnalysisScripts v0.2.0 and Heasoft v6.15.1.

Based on the binned as well as unbinned likelihood analysis results for the total energy range, no statistically significant detection was made of AE Aquarii within the selected region of interest (ROI). Refer to Figure 6 for a false colour map of the binned likelihood analysis. The indicated regions in yellow is relevant detected sources from the 2nd Fermi Catalogue. The regions in white were used in the following analysis procedures, with the ROI of AE Aquarii and selected test zones indicated. The test zones was selected to cover a range of gamma-ray sky background densities as well as distances from the target ROI to broaden the sample population used during the testing of the analysis methodology. All of these region sizes were set at 2 degrees, to specify the size of the error box as defined for the 2nd Fermi Catalogue.

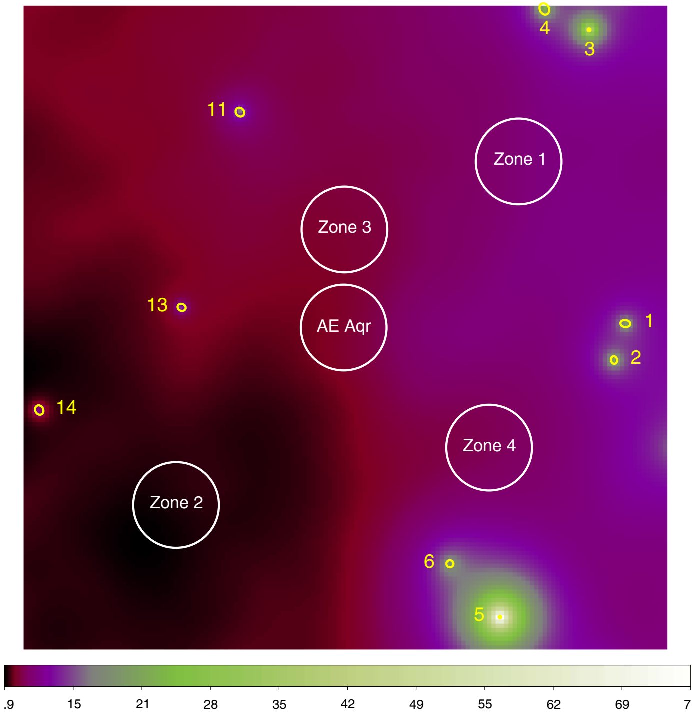

Figure 6: Likelihood analysis map for the region centred on AE Aquarii. Indicated in yellow are relevant Fermi detected sources from the 2nd Fermi Catalogue. Also indicated in white are the selected ROI of AE Aquarii as well as selected test zones used during the testing of the analysis methodology.

Based on the likelihood analysis, a different methodology was undertaken in the form of periodogram analysis of the dataset to determine if any pulsed modulation at or close to the fundamental (33.08 s) and first (16.54 s) harmonics were visible within the data. The argument for the search was based upon a report [13] that the WD in AE Aquarii could possibly behave like a spun-up pulsar, as well as earlier reports of possible GeV and TeV emission at these periods [15, 16, 17], although QPO-like features close to these periods were also found. Therefore the "gptsearch" tool was used with the following parameters: A Rayleigh analysis was done with a step size of 5000 (2.97×10^{-5} Hz) times the Fourier resolution (5.94×10^{-9} Hz), considering the very long baseline time. The number of trails were set to 2000 around 40 mHz to cover the frequencies 10-70 mHz. The resultant power spectrum, with the noise level set at 4σ as recommended for *Fermi*-LAT data, was examined for any power at the specified WD frequencies (Figure 7).

A power peak (16.5398 s) that corresponds within error with the first harmonic was found between the 3σ and 4σ levels, with a very strong QPO-like feature (16.507 s) next to it (Figure 7).

To consider the noise versus signal distribution of the power peaks of the resultant spectrum, a histogram of $\log_{10}(\mathrm{dN}/\mathrm{dZ})$ versus the Rayleigh statistic Z was plotted. As can be seen from Figure 8 the power spectrum values correspond to white noise.

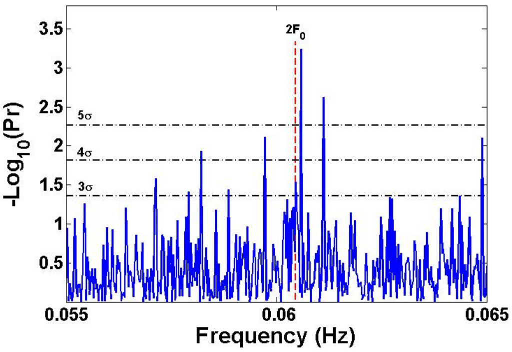

Figure 7: Rayleigh -Log_{10}(Pr) spectrum centred on the first harmonic (indicated by red dashed line) for the WD spin period for AE Aquarii, between energies of 250 MeV and 300 GeV.

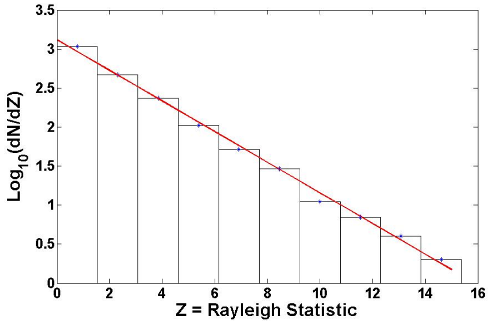

Figure 8: Histogram of the Rayleigh Z distribution for AE Aquarii, between energies of 250 MeV and 300 GeV.

From these results it is concluded that if any viable low level modulation from AE Aquarii is detectable with the *Fermi*-LAT it will be within the noise level. The occurrence of this peak through different energy bins was therefore tested. This was accomplished by producing power spectra for the different selected energy bins, i.e. 250-500 MeV, 500-750 Mev, 750-1000 MeV, 1-10 GeV, 1-100 GeV and 1-300 GeV. By sampling possible signal peaks, i.e. all peaks at powers greater than 4σ, and determining the distribution of those peaks through the different energy bins, any possible consistent low level modulation could be identified. This is based on the assumption that white noise will have a random distribution through the different energy bins, while a consistent low level modulation will be stable and have an occurrence of $> 4\sigma$ in distribution through the different energy bins. Refer to Figure 9.

As can be seen from Figure 9, a low level peak is visible within the noise structure for the region centred on AE Aquarii. To test the validity of the technique used and the results obtained, the same analysis methodology was applied to the four test zones indicated in Figure 6. No similar structure was found for any of the test zones between the test frequencies of 10-70 mHz, thus indicating that the proposed low level power is not due to the analysis methodology, but is inherent to the data analysed.

With no statistical likelihood source detection, for determination of flux values, made within the Pass-7 LAT data based on the recommended techniques, upper-limit values at the 95% confidence level were determined for the energy bins considered, for inclusion into a SED for AE Aquarii. These *Fermi*-LAT upper-limits, along with determined *Suzaku* flux and selected values from previous studies were then included into a SED for AE Aquarii. Also included were sensitivity response curves for selected instruments. The difference between the 2-year instrument response curve for *Fermi*-LAT and the determined upper-limit values for AE Aquarii, is due to the cumulative effect

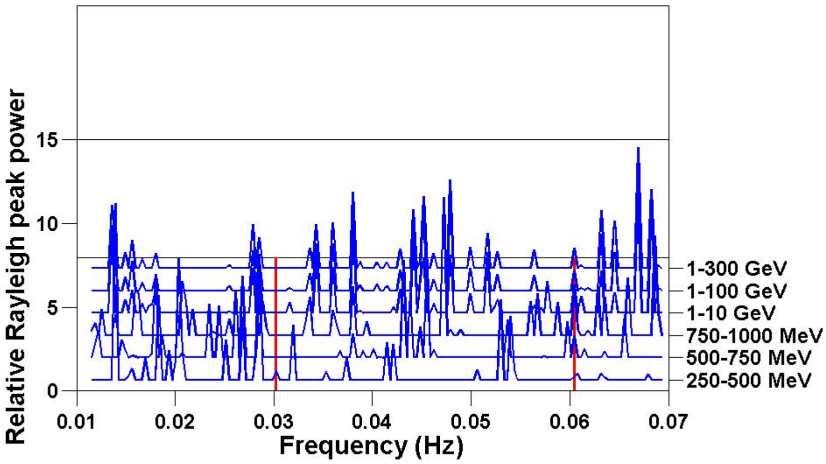

Figure 9: Sampled Rayleigh peaks with power above 4σ for selected energy bins for AE Aquarii. The fundamental frequency and first harmonic of the current model WD spin period is indicated in red.

from the dataset length of ~ 5 years used. This means that for the calculation of the sensitivity curve the longer the dataset used, the more counts is available to refine the sensitivity model and thus lowering the lower limit for detectable energy for the Fermi-LAT instrument. The opposite is then applicable to upper-limit energy ranges, i.e. the longer the dataset length the more counts is available, which increases the likelihood of a positive detection, thus increasing the upper-limit energy range. Any emission from the source, if detectable, would then be somewhere between the sensitivity curve and the upper-limits. Refer to Figure 10.

4. Final discussions and conclusion

Based on the results from the *Suzaku* spectral analysis that indicates a possible Bremsstrahlung component in conjunction with a power law spectrum, the possibility exists for a population of free charged particles that can be accelerated to higher energies. This result, along with the possible low level power (16.5386 ± 0.02323 s) observed at the first harmonic of the WD spin period, shows that the possibility of non-thermal high energy emission in AE Aquarii cannot totally be excluded.

A renewed effort is therefore called for studies utilising newer and more sensitive VHE instruments, such as CTA, in conjunction with multi-wavelength analysis techniques, to resolve whether AE Aquarii could be an emitter of pulsed emission at energies $\varepsilon_\gamma > 10$ keV under certain conditions.

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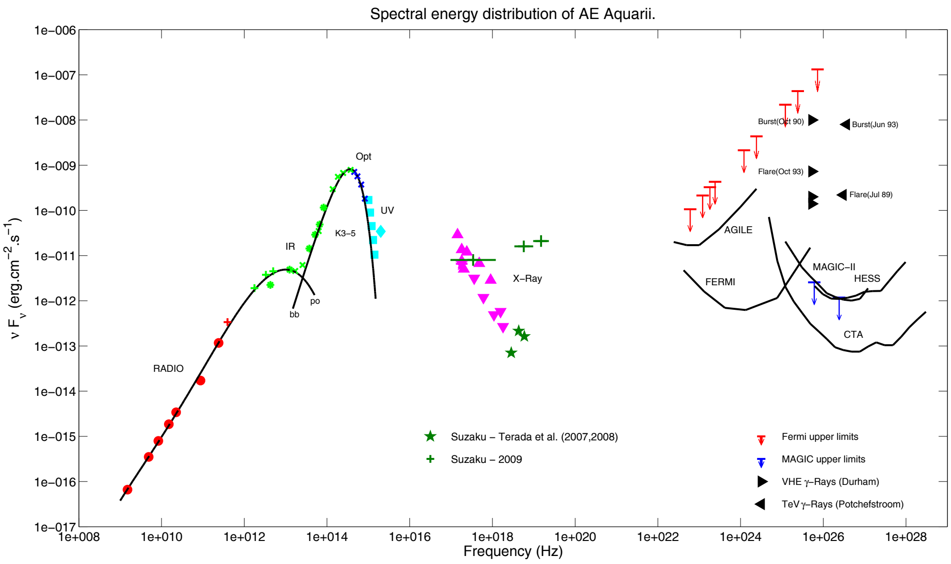

Figure 10: Updated SED for AE Aquarii, including newly calculated flux and upper-limit values for *Suzaku* and *Fermi*-LAT data. The sensitivity curves for selected instruments are indicated, i.e. AGILE (1 year), Fermi (2 years), MAGIC-II (50 hours), HESS (50 hours) and CTA (Theoretical 50 hours). The values included for the Potchefstroom and Durham groups were for experiments conducted using the Nooigedacht Mk I Cherenkov telescope [15] and the University of Durham VHE gamma-ray telescope at Narrabi, N.S.W., Australia [17] respectively.

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