Possible pulsed γ-Ray Emission from AR Scorpii and AE Aquarii using Fermi LAT Data.

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AE Aquarii

- Consist of a magnetic white dwarf and a K4-5 V main sequence star
- Orbital period 9.88 hours, spin period: 33.08 seconds
- Mass transfer and ejection from the secondary star due to rapid white dwarf spin

- Multi-wavelength emissions across the electromagnetic spectrum
- Radio flares caused by synchrotron radiation from accelerated particles
- Optical flares can increase brightness by several magnitudes
- X-ray pulsations from accretion and magnetic interactions
- Reports of gamma rays

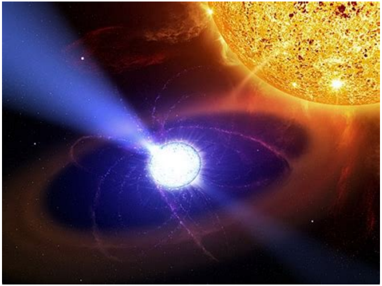


Figure: Artistic impression of AE Aquarii.

AR Scorpii

- Consists of a white dwarf with spin 117 seconds and a red dwarf star
- Unique pulsations every 117 seconds from the white dwarf's relativistic beam sweeping across the red dwarf
- Non-thermal, pulsed, and polarized emissions indicating strong magnetic activity

- Unique pulsations every 117 seconds from the white dwarf's relativistic beam sweeping across the red dwarf
- Non-thermal, pulsed, and polarized emissions indicating strong magnetic activity

- Emissions range from radio to X-rays

Figure: Artistic impression of AR Scorpii.

Reduction and analysis of Fermi LAT data
Binned likelihood

- We selected photons with energies in the energy range 0.1-500 GeV from a 10° radius region of interest (ROI).
- We used the P8R3_SOURCE_V2_v1 set of response functions and selected corresponding source-class events, event class (evclass=128) and FRONT+BACK event type (evtype=3).
- Events with zenith angles below 90° were chosen to avoid contamination from Earth's limb (cosmic ray interactions with the atmosphere).
- Applied good time intervals (GTIs) based on spacecraft positions.
- Generated necessary livetime cube and exposure maps for further analysis.
- Binned likelihood (Mattox, 1996) analysis was performed for both AR Scorpii and AE Aquarii using the Fermi Science Tools software packages (v11r0p5, gtlike/pyLikelihood routine).

Rayleigh test and Tempo2 Fermi plug-in

- Events in the energy range of 0.1-50 GeV within a ROI of 0.6° were utilized, varying the lower limit from 100 to 2000 MeV in increments of 100 MeV.
- The periodic search was performed using *gtpsearch* of the Fermi Science Tools software packages (v10r0p5).
- Pulse phase were applied to each event using the Fermi plug-in and Tempo2 tool (Hobbs, 2006).
- To assign phases using Tempo2 the entire data-set was considered but varying energy ranges.
- These tools conduct the barycentric correction of each photon's time of arrival utilizing the Fermi-LAT spacecraft file and coordinates of the source of interest.

Results and Discussion

- No pulsed or steady gamma ray emission were detected above 3 σ from AE Aquarii using standard events selection only.
- Using Binned likelihood analysis, indications of gamma-ray emission $\approx 3\ \sigma$ were noticed in AR Scorpii.
- Pulsed γ-ray emission was detected using *gtpsearch* and *tempo2*.
- The emission originated from a ROI with a 0.6° radius around AR Scorpii, in the energy range 2-50 GeV.

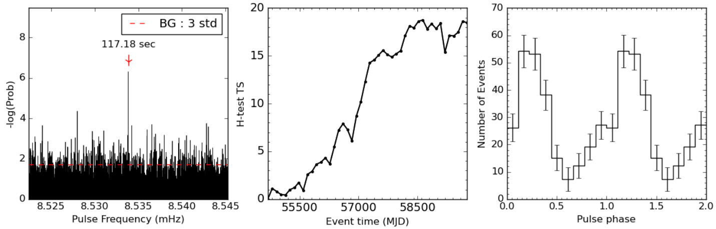


Figure: Left: The Rayleigh test shows a pulsed modulation at the white dwarf's spin period, with a 6.3 sigma significance, ruling out noise with 99.99995% confidence. Middle: H-test. Right: Gamma-ray phase light curve.

TS-gating and summed likelihood

- Events selection with TS-gating (is similar to phase-gating):
  - The entire data set is divided into 5-day bins, and an unbinned likelihood analysis is performed for each bin.
  - Events are selected from time bins where TS is above zero.
- Binned Likelihood of TS-gated data:
  - Events from time bins with TS above zero were selected.
  - Binned likelihood was conducted using these events.
- Summed likelihood:
  - Improves results when front and back summed together.
  - Used in this study along TS-gating.
  - The Binned likehood of time bins with TS above zero were summed together.

	AE Aquarii	AR Scorpii
TS	206.95 ($sig_{corr} \geq 5\sigma$)	197.20 ($sig_{corr} \geq 5\sigma$)
Npred	1330.94	1841.63
Flux	3.506e-08 $\pm$ 4.37e-09	5.152e-08 $\pm$ 7.54e-09
EnergyFlux	1.066e-05 $\pm$ 9.74e-07	2.037e-05 $\pm$ 2.06e-06

AE Aquarii Spatial Maps

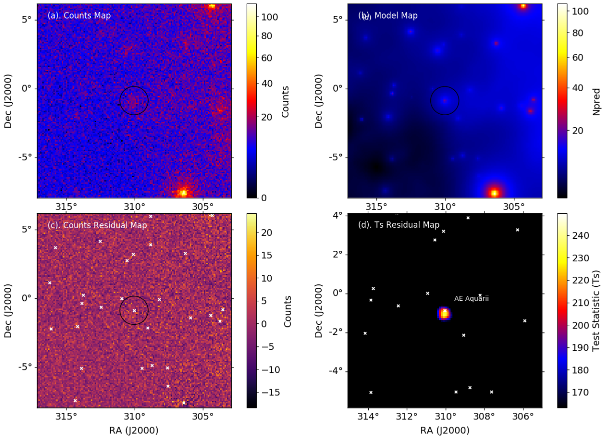


Figure: (a) Observed counts map, (b) model-predicted counts map, (c) counts residual map (d) TS residual map.

Spectral Energy Distribution of AE Aquarii

- The energy flux spectrum plot of AE Aquarii showing a power-law model distribution with an index of 1.8 ± 0.92.
- The emission is mainly restricted to lower energy bins $\epsilon_\gamma \leq 10\,\text{GeV}$.

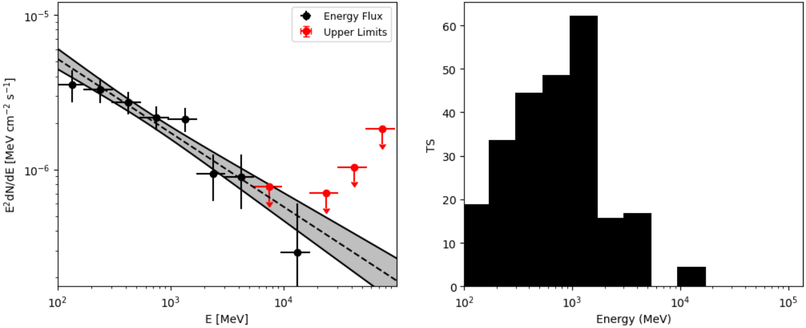


Figure: Left panel: Generated through binned analysis from events selected using TS gating, as briefly discussed earlier. Right panel: The corresponding significance distributed as a function of energy for each energy bin with a measurable signal.

AR Scorpii Spatial Maps

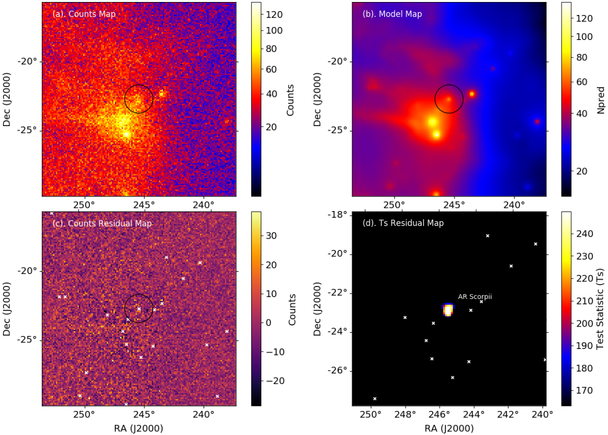


Figure: (a) Observed counts map, (b) model-predicted counts map, (c) counts residual map (d) TS residual map.

Spectral Energy Distribution of AR Scorpii

- The energy flux spectrum follows a power-law distribution with an index of 2.0 $\pm$ 0.86.
- The right panel illustrates the significance of the signal as a function of energy for each measurable energy bin.
- Emission is primarily constrained to energy bins where $\epsilon_\gamma \leq 10$ GeV.

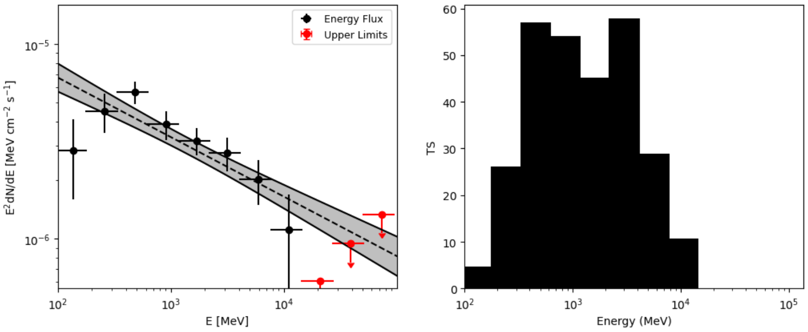
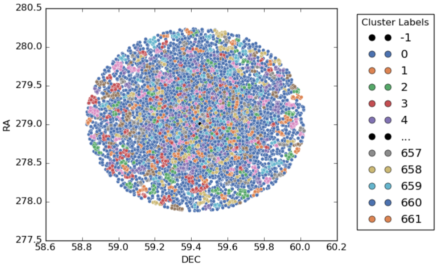


Figure: Energy flux spectrum and significance distribution of AR Scorpii.

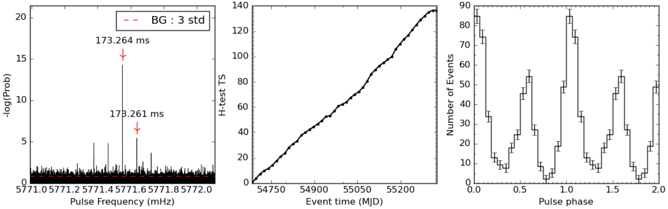
HDBSCAN Clustering
PSR J1836+5925

- Fermi tools like *gtsrcprob* were ineffective to faint sources, i.e., we chose to use HDBSCAN clustering.
- The pulsar PSR J1836+5925 is used as test source.
- Events are selected from a ROI with 0.6° radius around PSR J1836+5925.
- RA, DEC, ENERGY, THETA, PHI, EARTH_AZIMUTH_ANGLE, TIME, and LIVETIME associated with each event were used to cluster

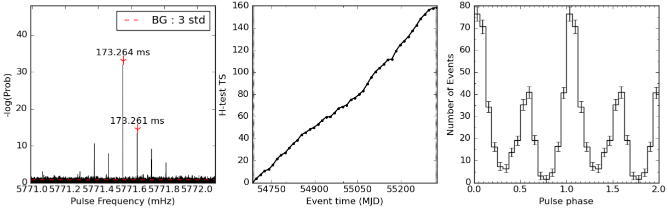
- The existing timing model of PSR J1836+5925 is used to calculate the phase of each event using Tempo2.
- The events of clusters with phase light curve similar to the expected were selected to produce the final event file.
- Then, the final event file was used to conduct the timing analysis using Tempo2, and gtpsearch.



PSR J1836+5925

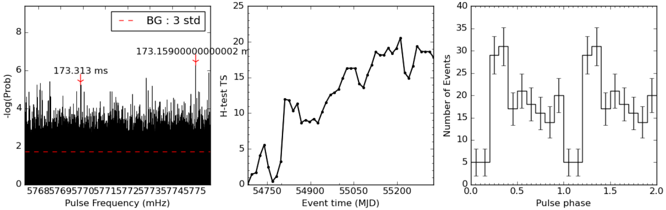


(a) These plots were produced from 11675 events, the total events in a ROI of 0.6° radius, Left: Rayleigh power spectrum, Middle, H-Test spectrum, and phase light curve.

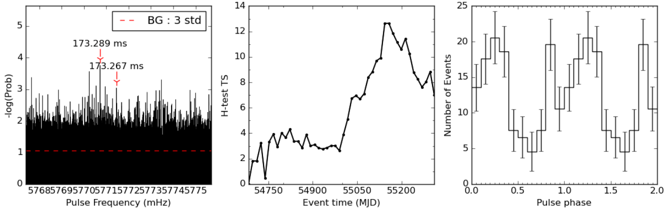


(b) These plots were produced from 8234 events selected using HDBSCAN clustering in a ROI of 0.6° radius, Left: Rayleigh power spectrum, Middle, H-Test, and phase light curve.

PSR J1836+5925



(a) Rayleigh test spectrum (left), H-test (middle), and light curve (right) for PSR J1836+5925 at 15 degrees away from the center (right side)..



(b) Rayleigh test spectrum (left), H-test (middle), and light curve (right) for PSR J1836+5925 at 15 degrees away from the center (left side).

Pulsed γ-ray signal from AE Aquarii

- Photons in the 0.1-50 GeV extracted from a ROI with a radius of 0.6°.
- Modulation at 33.08 s with $P \sim 1.77 \times 10^{-7}$, significance: 6.75 σ.
- Modulation at the second harmonic (16.54 s) also detected with $P \sim 7.27 \times 10^{-7}$, significance: 6.13 σ.
- Light curve folded using De Jager et al. (1994) ephemeris.

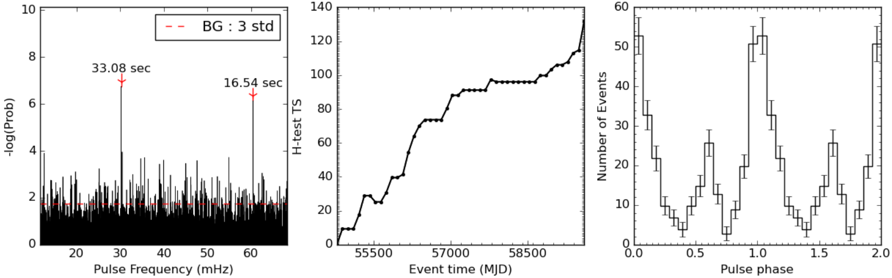


Figure: Left: Rayleigh test power spectrum. Middle: H-test plot showing TS accumulation over time. Right: Gamma-ray phase light curve.

Pulsed γ-ray signal from AR Scorpii

- Events (1-50 GeV) selected using HDBSCAN clustering.
- Rayleigh test power spectrum shows a significant spike at 117 s (chance probability: $P = 1.49 \times 10^{-7}$, 6.8 σ).
- Light curve of AR Sco folded at 117 seconds (Marsh et. al 2016), with photons from a 0.6° ROI.

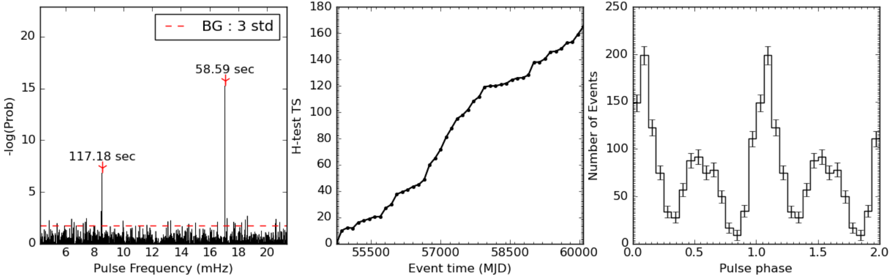


Figure: Left: Rayleigh test power spectrum. Middle: H-test plot showing TS accumulation over time. Right: Gamma-ray phase light curve.

Conclusion

- Utilizing TS-gating alongside binned likelihood in the Fermi LAT data in the energy range of 0.1-500 GeV we detected gamma-ray emissions from AE Aquarii and AR Scorpii.
- It is noticeable from energy flux spectrum that gamma intensity is observed at lower energy (0.1-10 GeV).
- HDBSCAN clustering allowed an effective selection of events which resulted in improved significance of AE Aquarii and AR Scorpii.
- In future, we would like to use complex models to effectively fit the detected signal
- We would like to improve HDBSCAN clustering pipeline to use it alongside Binned and unbinned likelihood.