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A preliminary All-sky search of Flaring and transient in the TeV gamma-ray sky observed by HAWC

PoS(ICRC2025)674

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The long-term operation of HAWC provides valuable opportunities to study transient and variability phenomena in sources emitting at TeV energies. In this work, we introduce the All-sky Root around in an Unbiased way (ARU) algorithm, a tool designed to estimate the significance of deviations from constant emission on different timescales using data from ground-based gamma-ray observatories. We compute the expected sensitivity of ARU for HAWC data. Finally, we present preliminary results on flaring sources detected within HAWC's field of view and their corresponding variability indices

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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1. Motivation

The long-term data-set obtained after 10 years of operation of the HAWC Observatory give us the opportunity to investigate variability and search for transient phenomena at daily, monthly or even annual timescales. However, most of the searches have been limited to already observed transient events and sources with known variability. Between them, Active Galactic Nuclei (AGN) and compact binary systems have been observed with variations in their flux at daily and weekly timescales at TeV scales.

Additional information can be obtained from all-sky searches as it is demonstrated by the Fermi-LAT All-Sky Variability Analysis (FAVA) catalogs [1, 2]. The FAVA approach consists on estimating the significance of deviation of observed counts for a short term with respect to the constant flux hypothesis derived from long-term observation of the gamma-ray (γ-ray) sky. Thus, any deviation from the constant flux is interpreted as evidence of transient or flare activity for a source. See [1] for more details. This FAVA methodology does not depend on any modeling of the diffuse emission, and does not assume any spectral shape for the transient and variable sources. Spectrum information of the variable sources found can be obtained by complementary analysis.

2. The ARU Approach

In more detail, if we assume that the γ-ray emission observed during a long-term (let's say 10 years), is constant on time, then we can estimate the expected observed counts for any period smaller than the total duration time using a scaling factor $\varepsilon(E, \theta, \phi, ...)$ that depends on the energy of the observed counts, the zenith, and azimuth angles, and possibly on another set of parameters related to the observatory itself. Then, we can compare actual observed counts for a period with the same duration as our estimate, and quantify the significance of the deviation with respect to the expected counts. From here, we can see that constant emissions, either from γ-ray or CR-ray origin, cancel each other; and if the comparison results in small deviations $\lesssim 3\sigma$, the emission for a region of interest (ROI) is consistent with constant emission for that period.

In the case of the Fermi-LAT experiment, the exposure depends on the energy of the γ-ray events and the observation angles. Additionally, the expected counts are obtained from simple adding up the different energy bins.

Unlike Fermi-LAT, the HAWC data is binned according to the fraction of PMT hit during an event, and hence, it is not obvious to simply add the different fHit maps. We adapt the FAVA methodology for HAWC in the following way:

First, we obtain the maps for different short terms (weekly, biweekly, and monthly) for the entire operation time of HAWC. With both, the long- and short- term maps, we apply a top-hat smoothing to the observed counts maps using the 68% angle containment of the PSF. We do the same for the bkg maps, but using a smoothing angle of 5 degrees. Once we have the smoothed long- and short-term maps for bkg and counts, we compute the scaled (or expected) maps with the ratio of the short-term bkg counts to the long-term bkg counts.

To estimate the significance of the deviation of the observed counts with respect to the scaled maps on a short-term period; we employ a likelihood-ratio test (TS statistic, hereafter) with the following definitions:

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- The null hypothesis refers to the scaled counts. Then, we compute the likelihood of have observed counts (n^{ST}_{obs}) with respect to the expected counts (κ_{scal}):

$$H_{null} = Poisson(n|b) = Poisson(n^{ST}_{obs}|\kappa_{scal}). \quad (1)$$

- Alternative hypothesis should be the number of counts from the expected plus the counts due to the possible flare/variability of the sources in a ROI: $\kappa_{obs} = \kappa_{scal} + \delta_{var}$. Here, we make the extra assumption that $\kappa_{obs} = n^{ST}_{obs}$. And the likelihood for the alternative hypothesis is:

$$H_{alt} = Poisson(n|s + b) = Poisson(n^{ST}_{obs}|\kappa_{obs}). \quad (2)$$

We can then construct the likelihood-ratio test with the following definition:

$$TS = -2\ln\left(\frac{H_{null}}{H_{alt}}\right) = -2\ln\left[\frac{P(n^{ST}_{obs}|k_{scal})}{P(n^{ST}_{obs}|\kappa_{obs})}\right]. \quad (3)$$

The previous definitions assure that we can add up the different fHit bins, and compute the total (Gaussian) significance map.

The meaning of the TS derived from the hypotheses provided here is to estimate the deviation from constant emission (for the source). Then, a TS equals to zero for a certain period and position, means that the emission is consistent with being constant in both the short- and long-term periods.

The software dedicated to estimate the significance of deviations from the constant emission at different timescales is called ARU: All-sky Root around in an Unbiased way.

3. ARU sensitivity for HAWC

We estimate the sensitivity of ARU to the case of HAWC data. We simulate sources with two emission components: a steady constant component, described by a Simple Power Law (SPL) with spectral index of 2.63; plus a high emission state described also by a SPL with spectral index of 2.63. We generate fake expected and observed counts maps for weekly and monthly timescales. For each map, we inject 12 sources along a declination band centered at 25 deg (where HAWC's sensitivity is maximal). The expected maps only consider the steady constant emission, while the fake observed include the constant plus the high emission state. The normalizations at 1 TeV of the steady component are chosen from 10 different values between 10^{-15} TeV^{-1} cm^{-2} s^{-1} and 2.6×10^{-13} TeV^{-1} cm^{-2} s^{-1}. In the other hand, normalizations at 1 TeV for the high emission states are randomly chosen in the range from 10^{-14} TeV^{-1} cm^{-2} s^{-1} and 2.6×10^{-13} TeV^{-1} cm^{-2} s^{-1}. We generate a total of 100 repetitions. For each value of steady component, we ended with 1200 values of different high emission states. Then, we applied ARU to each map and got the deviation significance (σ_{ARU}) maps.

For each normalization of the constant emission we computed the normalization of the high-emission/flare component where σ_{ARU} reaches a value of 5. Figure 1 shows the expected differential and integrated sensitivity of ARU applied to HAWC data.

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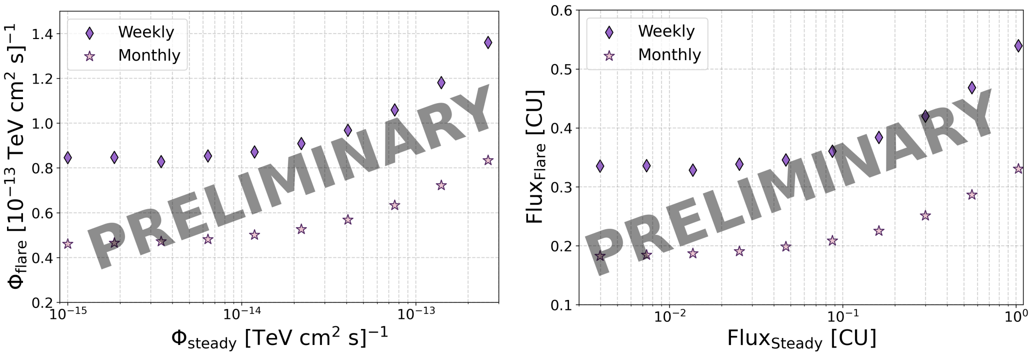

Figure 1: ARU Sensitivity to HAWC data. **Left.** Differential flux sensitivity in the space of flare normalization vs steady normalization. The purple diamonds and pink stars show the expected sensitivity to weekly and monthly timescales respectively. **Right.** Integrated (between 1 and 100 TeV) flux sensitivity.

4. Results and discussion

We present preliminary results derived from the search of flaring sources using ARU. We got the $\sigma_{\rm ARU}$ maps for three different timescales: weekly, biweekly and monthly. However we will center our presentation and discussion to weekly timescales. Figure 2 shows the $\sigma_{\rm ARU}$ significance curve of four different sources within the field of view of HAWC. The two top pannel correspond to the case of two known variable AGNs observed previously with HAWC: Mrk 421 and Mrk 501. For both cases, reddish orange crosses highlight periods where the deviation from the constant emission has a significance greater than 5 ($\sigma_{\rm ARU} > 5$). From a visual inspection, we can see that Mrk 421 has periods that deviates significantly from the "constant emission" estimated from the long-term integrated maps. A more detailed analysis of the Mrk 421 high-emission states is in progress. In the case of Mrk 501, we observe that only one period shows significant deviation from constant emission. In the other hand, the two bottom panels show the significance curves for the Crab Nebula an M 87. Both of them are consistent ($|\sigma_{\rm ARU}| < 3$) with constant emission during the 10 years of HAWC observations. In the case of M87, a flare was detected during 2018 [3], however our weekly $\sigma_{\rm ARU}$ maps does not show evidence of such activity. Analysis at smaller timescales is being considered.

5. Conclusions

Here, we present the methodology behind ARU to search for flaring sources at the TeV sky and its expected sensitivity when applied to HAWC data. We also show the $\sigma_{\rm ARU}$ significance curves for four different sources to show the capabilities of this tool. For the case of Mrk 421, we observe that this source has undergone different flaring/high emission episodes during the 10 years of data. On the contrary, M 87 does not show evidence of variable behavior, at least at weekly timescales at TeV energies.

The approach we described and coded in ARU is important for future All-sky searches of flaring episodes of extragalactic and galactic sources. ARU can be easily adapted to the data from high duty-cycle observatories as the future SWGO. ARU also provides a good complementary tool to analysis software as `gammapy`. More updates coming soon.

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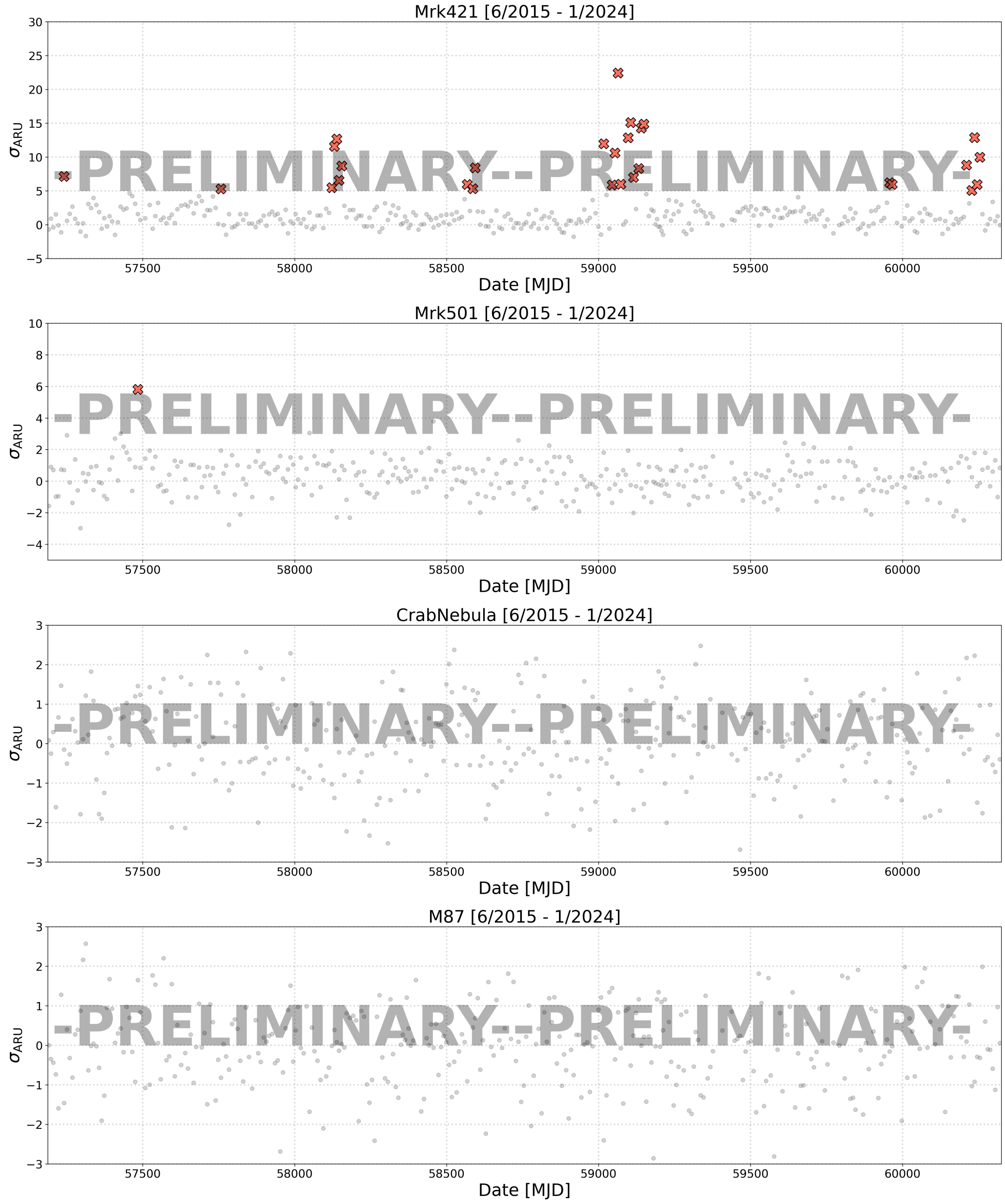

Figure 2: Weekly ARU significance curves of four different sources in the field of view of HAWC. From top to bottom: Mrk 421, Mrk 501, the Crab Nebula and M87. Reddish orange crosses represent periods where σ_{ARU} is larger than 5, likely related to high-emission or flaring states of the source in question.

References

[1] M. Ackermann, M. Ajello, A. Albert, A. Allafort, E. Antolini, L. Baldini et al., *The fermi all-sky variability analysis: A list of flaring gamma-ray sources and the search for transients in our galaxy*, The Astrophysical Journal **771** (2013) 57.

[2] S. Abdollahi, M. Ackermann, M. Ajello, A. Albert, L. Baldini, J. Ballet et al., *The Second*

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Catalog of Flaring Gamma-Ray Sources from the Fermi All-sky Variability Analysis, *The Astrophysical Journal* **846** (2017) 34.

[3] H.E.S.S. Collaboration:, Aharonian, F., Ait Benkhali, F., Aschersleben, J., Ashkar, H., Backes, M. et al., *Curvature in the very-high energy gamma-ray spectrum of m 87*, *A&A* **685** (2024) A96.

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