GAMMA-RAY FOLLOW-UP OBSERVATIONS OF DWARF NOVA AT2021afpi AS A POSSIBLE NEUTRINO COUNTERPART WITH THE VERITAS INSTRUMENT*

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AT2021afpi was a 10 mag outburst seen by the MASTER-Tavrida auto-detection system in temporal coincidence with the astrophysical neutrino candidate IC211125A. The object was observed as an optical bright transient, initially classified as a classical nova. Follow-up observations by the VERITAS instrument at gamma-ray energies > 100 GeV on the nova location resulted in no detection for an exposure of 5.5 hours. Further spectroscopic reports reclassified AT2021afpi as a dwarf nova of the type WZ Sge-Type, which are not expected to be neutrino emitters. A possible blazar detected by *Fermi*-LAT, 4FGL J0248.0+2232, which lies within the 90% localisation region of IC211125A, was observed in a flaring radio state four days after the neutrino alert. A further combined analysis with 1 hour of exposure time on 4FGL J0248.0+2232 at the position of AT2021afpi still resulted in no detection.

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1. Introduction

Novae were firmly established as gamma-ray (> 100 MeV) sources by *Fermi*-LAT observations of several outbursts, *e.g.*, V407 Cyg 2010 [1]. The recent detection of gamma-rays from the 2021 outburst of the recurrent symbiotic nova RS Ophiuchi by the MAGIC and H.E.S.S. telescopes [2, 3] allowed the first characterisation of the gamma-ray emission from a nova in the very-high-energy (> 100 GeV) range. Such observations instigate the search for new novae observations with ground-based gamma-ray telescopes.

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The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of Imaging Atmospheric Cherenkov Telescopes (IACTs) dedicated to the VHE gamma-ray astrophysics in the 80 GeV to 30 TeV energy range. Located at the Fred Lawrence Whipple Observatory in Arizona, USA, it is composed of an array with four telescopes of 12 m in diameter each. For gamma-rays with 1 TeV, it has an energy resolution of 17% and angular resolution of 0.08 degrees. A source with about 2.5% of the Crab strength can be detected with 5σ in about 5 hours [4].

An inevitable rate of background events, composed mainly of cosmic-ray events which produce gamma-ray-like images, pass the selection cuts and, therefore, limit the achieved sensitivity. Depending on the source type and strength, and the observation conditions, an enhanced rate of gamma-ray-like events is observed when an astrophysical object is in the field of view (FoV) of the telescope. With transient events, an increase in the observed rate of events happens at an unknown time and position in the FoV.

Gamma-ray emission in transient sources, like classical novae, could be derived either by the leptonic mechanism, when relativistic electrons Compton up-scatter optical photons or emit bremsstrahlung radiation, or via the hadronic mechanism, which is powered by shock interactions [5]. During thermonuclear explosions, material is ejected from the outer layers of white dwarfs as they accrete mass from a red giant companion. The ejecta drives an expanding shock into the wind of the companion star, promoting the acceleration of particles to relativistic energies. When the accelerated ions collide with the particle background, pions are produced and ultimately they decay, producing a neutrino ($\pi^{\pm}$) and gamma-ray (π^0) emission.

According to the calorimetric technique, at the time of peak optical emission, the non-thermal gamma-ray emission might be proportional to the shock-powered optically radiated energy [5]. The time-correlated optical and gamma-ray emissions in classical novae, recently reported by *Fermi*-LAT [6], are a strong indication that shocks might have an important role in powering particle acceleration in novae. The simultaneity of flares indicates a common origin for both emissions.

2. Follow-up observations of IC211125A with the VERITAS array

On 25 November, 2021, at 06:22:21.56 UT, the ICECUBE Astrotrack Bronze alert stream selected a track-like astrophysical neutrino candidate, IC211125A [7]. A 10 mag outburst, AT2021afpi (also known as MASTER OT J030227.28+191754.5), was detected as a possible counterpart during follow-up observations by the MASTER-Tavrida auto-detection system [8] at RA (J2000) 45.61° and DEC (J2000) 19.30° [9].

At the time of discovery, the unfiltered bolometric magnitude of AT2021afpi was 15.1 mag. The source brightened up to 13.5 mag 5 hours later, as reported by subsequent observations made by MASTER-OAFA and up to 11.7 mag, as seen by MASTER-Kislovodsk, 13 hours after the first discovery [9]. Besides the temporal coincident detection, the initially reported position was 0.76° from the edge of the 90% localisation region of the neutrino.

In a preliminary spectrum analysis, due to a hot blue continuum, strong Balmer lines and He I/II emission lines on its spectrum, AT2021afpi was initially classified as a classical He nova [10]. However, updated optical spectroscopy showed that He I/II lines shifted from single to double-peaked, with a peak separation of about 500 km/s, showing this object is more likely a dwarf nova. A time-series photometry for about 7 hours provided a period of 0.059 ± 0.002 day and amplitudes of 0.05 mag for the double-peaked modulations, which are strong characteristics of early superhumps [11]. Therefore, AT2021afpi was classified as WZ Sge-type dwarf nova.

Unlike classical novae, dwarf novae are powered by instabilities in the accretion disk and, therefore, are not expected to accelerate particles to relativistic energies [12]. In this scenario, dwarf novae would not host a neutrino emission due to hadronic interactions.

On 29 November, 2021, the TELAMON program [13], using the Effelsberg 100-m telescope of the Max-Planck-Institut für Radioastronomie, reported the radio flaring of 4FGL J0258+2030, which lies within the 90% localisation region of IC211125A. The source had flux densities of (91 ± 1.5) mJy at 14.25 GHz on 29 November and of (72 ± 3) mJy on 28 November, which are moderately higher than listed in the Radio Fundamental Catalog (RFC) (63 mJy at X band). 4FGL J0258+2030 was a very promising possible association because it was the first case of a gamma-ray bright Active Galactic Nucleus (AGN) consistent with two IceCube neutrino bronze or gold events, and because of the radio flare coincident with IC211125A.

Observations of AT2021afpi by the VERITAS instrument started on 28 November, 2021, in response to the IceCube alert, which appeared to be the onset of a He classical nova. In the next section, we describe the results obtained by the observations of IC211125A with the VERITAS instrument.

3. Results

The follow-up observations of IC211125A in the location of AT2021afpi by the VERITAS instrument started on 28 November, 2021, one day after the first brightening report of the nova. A total exposure of 5 hours and 29 minutes after quality examination was accumulated in 11 runs of 30 minutes each. The wobbling mode was used for the observations, with a 0.5 deg offset in each of the four cardinal directions.

The data were analysed assuming background rejection cuts optimised for a soft-spectrum source with the Boosted Decision Trees (BDT) method. The background is estimated from 6 OFF regions with the same size, shape, and offset to the FoV centre as the ON region.

The analysis yields no detection of the source above 0.24 TeV, with a statistical significance of -1.4σ, 82 events in the ON region, 579 events in the OFF region, and a background normalisation $\alpha = 0.17$. A sky map of statistical significance centred at the position of the source is shown in figure 1. An integral upper-limit for AT2O21afpi was determined with the Rolke method [14] for spectral index of 2.5, resulting 1.16×10^{-12} cm^{-2} s^{-1}, above 0.24 TeV with 95% C.L.

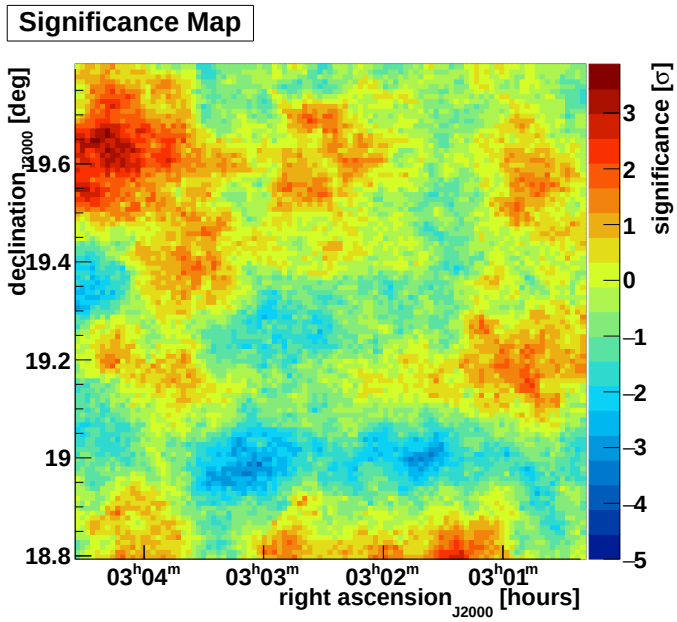

Fig. 1. Significance map centred at the position of AT2021afpi for 5 hours and 29 minutes of observation with the VERITAS array.

A total exposure time of 1 hour divided into 2 runs of 30 minutes each were taken in the wobble mode for 4FGL J0258+2030 on 30 November, 2021. The analysis resulted in no detection with significance of 1.5σ. A combined analysis of the datasets at the position of AT2021afpi for optimised soft cuts and reflected regions background yielded no detection with -2.1σ. An upper flux of 1.09×10^{-12} cm^{-2} s^{-1} (above 0.24 TeV with 95% C.L.) was obtained with the Rolke method. A sky map of statistical significance of the combined datasets centred at the position of AT2021afpi is shown in figure 2.

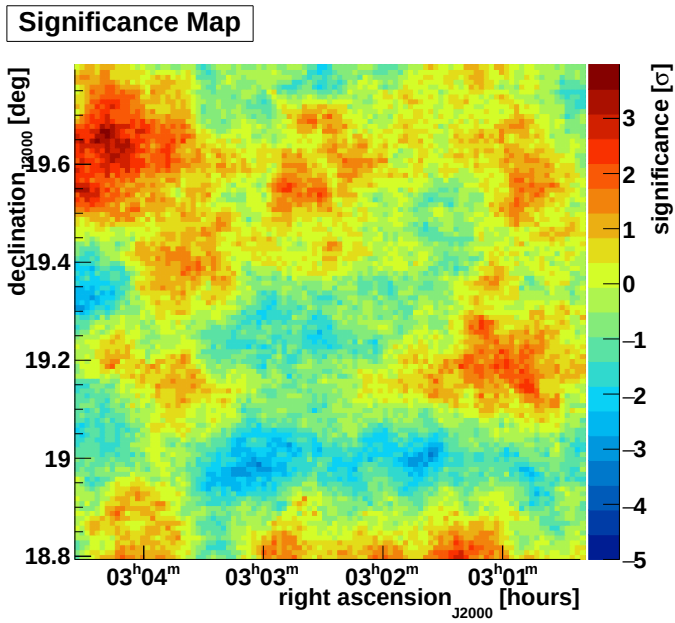

Fig. 2. Significance map for the combination of the AT2021afpi and 4FGL 0258+2030 datasets, centred at the position of AT2021afpi.

4. Conclusions

The VERITAS array is a part of the ground-based gamma-ray instruments in the hunt for very-high-energy emission from novae. Target-of-Opportunity (ToO) observations are a key part of transient observation with VERITAS. An exposure time of 20 hours is pre-approved for the 2021–2022 observation season in case a galactic nova trigger is reported by *Fermi*-LAT. On November 2021, the report of a probable astrophysical neutrino (IC211125A) was followed by a temporal-coincident detection of bright optical transient, AT2021afpi, initially classified as a classical nova and located just outside of the 90% C.R. of the neutrino. The VERITAS array carried on follow-up observations of the suspected nova, collecting 5 hours and 30 minutes of exposure time, which yielded no detection (-1.4σ) and an upper limit of 2.98×10^{-12} cm^{-2}s^{-1} above 0.24 TeV. Later reports updated the classification of AT2021afpi as a WZ Sge-type dwarf nova, which are not expected to be neutrino sources. Altogether, AT2021afpi is unlikely related to IC211125A. A second astrophysical source, 4FGL 0258+2030, was observed in a flaring state four days after the neutrino alert. Although it lies inside of the 90% C.R. reported by IceCube, 1 hour of exposure time taken with the VERITAS array lead to no detection. A further analysis of the combined datasets at the position of AT2021afpi also resulted in no detection with -2.1σ.

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