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Carpet-2 observation of E>300 TeV photons accompanying a 150-TeV neutrino from the Cygnus Cocoon

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We report on the observation of an excess of E>300 TeV gamma-ray candidate events in temporal and spatial coincidence with the IceCube high-energy neutrino alert consistent with the origin in the Cygnus Cocoon. The Cygnus Cocoon is a prospective Galactic source of high-energy neutrinos and photons. The observations have been performed with Carpet-2, a surface air-shower detector equipped with a large-area muon detector at the Baksan Neutrino Observatory in the Northern Caucasus.

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1. Introduction

The observation of astrophysical gamma rays have confirmed the existence of Galactic sources with energies above 100 TeV. In particular, there was offered a good candidate for a Galactic PeVatron [1] from the HAWK collaboration results [2, 3]. This is the site where particles are accelerating up to PeV energies and gamma radiations may be produced by interactions of energetic hadrons with ambient matter and radiation. Recent observations of the LHAASO collaboration discovered the existence of such Galactics PeVatrons [4]. They detected 530 photons in the energy range of 0.1 up to 1.4 PeV from 12 Galactic sources. But at the moment we cant unambiguously say about the generation mechanism of these photons and their cross observations with high-energy neutrinos that produced in the same sources will allow establishing their origin.

The first-mentioned of Cygnus Cocoon was in the work [5] by the Fermi-LAT collaboration. It is a superbubble around a region of active formation of massive stars, about 180 light-years across, located in the constellation Cygnus and contains two young star clusters Cygnus OB2 and NGC 6910. According to a work [6], it may be a site for cosmic-rays acceleration as a result source for neutrino and gamma-radiations of very high energy. However, the Cygnus Cocoon was associated with Galactic PeVatron in work [4] which makes it a motivated very high energy neutrino source.

On November 20, 2020, IceCube reported [7] about a candidate track-like neutrino event with an estimated energy of 154 TeV. The event was selected by the Bronze alert stream [8] with an average astrophysical neutrino purity is 30%. Inside the 90% of the localization region were several Fermi-LAT 4FGL sources [9] with the closest source is 4FGL J2028.6+4110e (Cygnus Cocoon). These alerts are routinely followed up by numerous instruments, in particular by the Carpet-2 gamma-ray telescope at the Baksan Neutrino Observatory [10]. This gives a chance to detect sub-PeV gamma rays co-produced with neutrinos, which cannot reach us from extragalactic sources because of pair production on cosmic microwave background radiation [11]. Standard Carpet-2 alert analysis revealed two gamma-ray candidate events in one-month intervals centered at the alert time [12]. In this article, we present results of a more detailed study of possible sub-PeV gamma-rays from the Cygnus Cocoon associated with the IceCube neutrino event.

2. The Carpet-2 EAS array and the Dataset

The Carpet-2 is an extensive air shower array located at the Baksan Neutrino Observatory, the North Caucasus. This array includes the Carpet array which consists 196 m^2 big square detector with 400 scintillators at the center. Also, it is separated into 25 units with 16 scintillators in each and used for the reconstruction of primary-particle energy from the shower size N_e. Five detectors, each of 9 m^2 areas with 18 scintillators. Four detectors located at 30 m distance and one is at 40 m distance from the array center. They are used for the arrival direction reconstruction from the time delay of the outer detectors. All those detectors use the standard liquid scintillator counters of 0.49 m^2 area and 30 cm thickness. An underground muon detector (MD) is located at a distance of 47 meters from the center of the Carpet array. The MD was equipped with a 175 (5 × 35) plastic scintillator with an area of 1 m^2 each (the scintillator thickness is 5 cm), attached to the ceiling of the MD tunnel. The rock absorber above detectors is equal to 500 g/cm^2, which corresponds to the threshold energy for vertical muons 1 GeV. The muon detector is used for selecting candidate

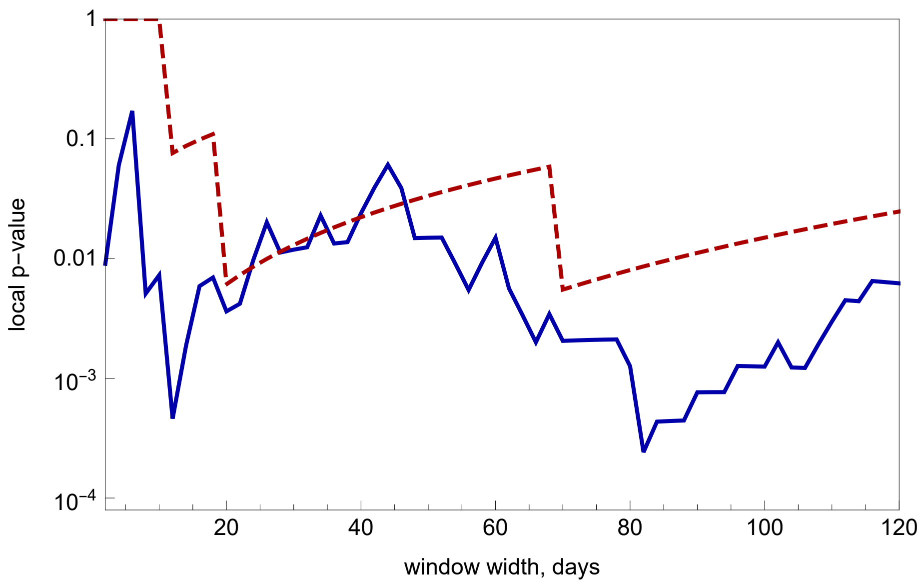

Figure 1: Dependence of the probability (p-value) on the width of the window centered on the neutrino arrival time (full line: all events, dashed line: photon candidates).

gamma-ray showers which are muon-poor. Some results, a description of the facility can be found in [13–15].

For the present study, we used Carpet–2 data recorded between April 7, 2018 and April 25, 2021, total 829 days of data acquisition. Standard quality cuts require that ≥ 500 GeV air-shower energy is deposited in Carpet; four outer stations participate in the determination of the arrival direction; the reconstructed shower axis is at least 0.7 m within the Carpet boundary; the reconstructed zenith angle is ≤ 40°. In total, 65703 events passed these cuts in this time period.

3. Data analysis and Results

The Monte Carlo simulation used by us is described in [16]. These simulations are used to relate the reconstructed shower size Ne to the primary gamma-ray energy E, to estimate the detection and reconstruction efficiency, and to develop criteria for separation between events induced by primary photons and by cosmic rays. The effective area of the installation as a function of energy is presented in [17].

In what follows, we concentrate on the circular region in the sky of this 4.7 angular radius, centered at the 4FGL J2028.6+4110e, associated with the Cygnus Cocoon, and call this region the Cygnus-Cocoon Circle (CCC). There is no excess from CCC over the expected background in the whole present Carpet-2 dataset. Therefore an upper limit on its integral gamma-ray flux was obtained: $I_\gamma(E_\gamma > 300\text{ TeV}) < 2.6 \times 10^{-13}\text{ cm}^{-2}\text{s}^{-1}$ (95% CL).

But we got a hint of a possible flare if we consider the events around the IceCube neutrino alert. In total, 346 events from the Cygnus Cocoon were registered, five of them are associated with photons candidates. To estimate the significance of the possible flare, an evaluation of the probability was carried out as a function of the window width with centering at the Ice Cube alert. Figure 1 shows those probabilities for all events and photon candidate events. Figure 2 presents the

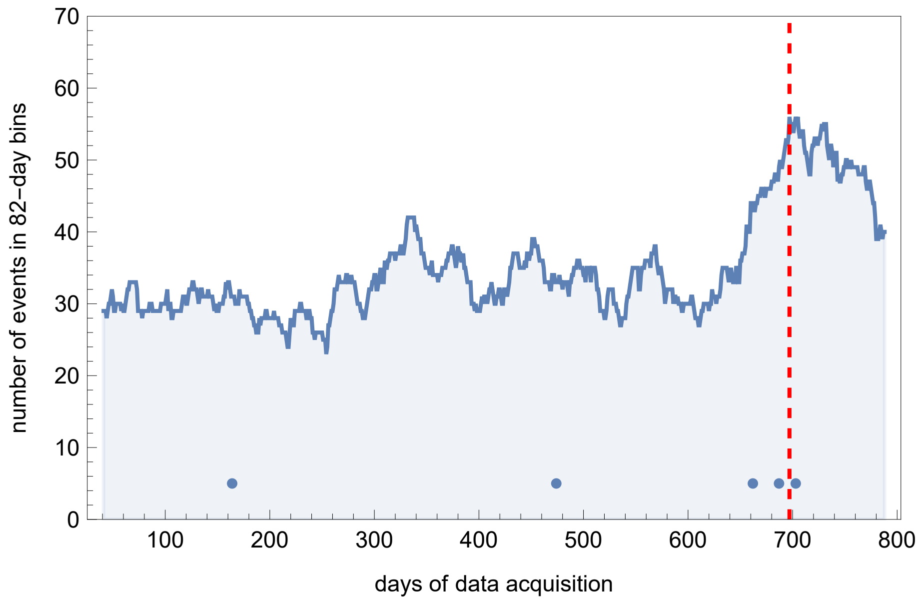

Figure 2: Number of events in $d = 82$-days bins centered at a given day of data acquisition for all events. Blue dots correspond to the time of arrival of gamma candidate events. The vertical dashed line indicates the neutrino arrival time.

number of events in a sliding window of the width d = 82 days of data acquisition centered at a certain date, as a function of this date for all events. One can clearly see the enhancement around the neutrino event, consistent between all events.

For the full set $p_{\text{pre}} = 2.4 \times 10^{-4}$ (3.67 σ pre-trial) at the $d = 82$, and for photon candidate are $p_{\text{pre}} = 5.5 \times 10^{-3}$ (2.78 σ pre-trial) at the $d = 70$. Also, an introduced correction for window-width trials based on the Monte-Carlo simulation reduces the statistical significance of the probable flare. After correction, we have $p = 1.5 \times 10^{-3}$ (3.17 σ post-trial) for all events and $p = 1.1 \times 10^{-2}$ (2.55 σ post-trial) for the photon candidate respectively.

4. Conclusion

An excess of events was observed by Carpet-2 from the direction of the Cygnus Cocoon region in temporal coincidence with the IceCube neutrino alert from the same direction. The statistical significance of the excess is 3.1 post-trial. For the first time, rare sub-PeV neutrino and gamma rays from the direction of a prospective Galactic PeVatron were observed in directional and temporal coincidence. This observation supports previously proposed scenarios of the origin of a part of observed high-energy neutrinos in pi-meson decays in Galactic sources.

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