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Targeted search for point sources of neutrons using data from the Pierre Auger Observatory(*)

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Summary. — Since the arrival directions of neutral particles point directly to their origin, they can be used to investigate sources of ultra-high-energy cosmic rays (UHECRs). The emission of UHECRs from a source is expected to be accompanied by the production of neutrons in its vicinity in nuclear interactions and via photo-pion production. Free neutrons undergo β-decay and travel a mean distance of $9.2\times(E/\mathrm{EeV})$ kpc. Therefore, neutron fluxes in the EeV range could be detected on Earth from sources of UHECRs in our Galaxy. Using cosmic ray data from the Surface Detector of the Pierre Auger Observatory, the largest cosmic ray detector in the world, we investigate neutron fluxes from Galactic candidate sources. Since we cannot distinguish between air showers initiated by protons and neutrons, a neutron flux could be identified as an excess of cosmic ray events around the direction of the candidate source. We look for excesses by comparing the observed signal with the background contribution. As candidate sources, we select objects of astrophysical interest, such as pulsars, microquasars, and magnetars. We also consider the Galactic center and the Crab Nebula as targets, as well as a subset of the gamma-ray emitters detected by LHAASO. We consider cosmic ray events with declinations from -90° up to $+45^\circ$ and energies starting at 0.1 EeV. Although we do not find evidence of a significant excess of events that could indicate a neutron flux from any of the tested targets, we establish the upper limit of the neutron flux in each investigated case.

1. – Introduction

One of the primary unsolved questions related to the study of ultra-high-energy cosmic rays (UHECRs) is identifying their origin. Neutral particles, unaffected by magnetic fields, serve as valuable probes for investigating UHECR sources. Any source emitting ultra-high-energy (UHE) protons should also generate UHE neutrons nearby through photo-pion production and other nuclear interactions. Given that air showers initiated

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by protons are indistinguishable from those generated by neutrons, we expect to detect localized excesses of events induced by a neutral particle flux originating from the direction of a neutron source. Free neutrons undergo β-decay with a mean lifetime of approximately 15 minutes. However, in the ultra-relativistic regime, neutrons can travel a distance of $9.2 \times (E/\mathrm{EeV})$ kpc, enabling their use as a tool for investigating Galactic sources of UHECRs.

Previous studies conducted by the Pierre Auger Collaboration on neutron searches [1, 2] did not identify significant evidence of neutron fluxes. These studies included events with zenith angles up to 60°. In this work, we extend the analysis, including events detected up to December 2022 with zenith angles up to 80°, thus expanding the field of view in declination from +20° to +45°. Additionally, we have lowered the energy threshold compared to those previous studies, decreasing from 1 EeV to 0.1 EeV

2. – Data sets

The Pierre Auger Observatory, situated in Malargüe in the province of Mendoza, Argentina, has a Surface Detector (SD) array consisting of 1,660 water-Cherenkov detectors (WCDs) distributed over approximately 3,000 km^2 [3]. The SD is surrounded by 27 fluorescence telescopes, composing the Fluorescence Detector (FD). Among the 1,660 WCDs, around 1,600 have a spacing of 1,500 m, while the remaining 60 are arranged in a denser configuration, covering an area of 24 km^2 with a spacing of 750 m. Hereafter, the data recorded by the larger portion of the SD array will be referred to as the "SD-1500 data set", and the data from the denser section as the "SD-750 data set". The duty cycle of the SD is about 100% and the FD is $\sim$ 15%.

The SD-750 data set was recorded from August 1, 2008 to December 21, 2022. The integrated exposure of the SD-750 array is 408 km^2 sr yr, resulting in around 1,500,000 events above 0.1 EeV. We split this data set into three independent energy ranges: $0.1 \leq E/\mathrm{EeV} < 0.2$, $0.2 \leq E/\mathrm{EeV} < 0.3$, and $E \geq 0.3$ EeV, besides the cumulative data set above 0.1 EeV. The SD-750 data set has events with a zenith angle up to 55°, resulting in declinations between −90° and +20°. The SD-1500 dataset was recorded between January 1, 2004, and December 31, 2022. Periods of instability in the array were excluded. The total exposure, after applying these cuts, was 110,000 km^2 sr yr, resulting in over 2,650,000 events with energies above 1 EeV. We perform the analysis into three independent energy ranges: $1 \leq E/\mathrm{EeV} < 2$, $2 \leq E/\mathrm{EeV} < 3$, $E \geq 3$ EeV, besides the cumulative data set ($E \geq 1$ EeV).

3. – Target sets

The targets are astrophysical objects candidates to produce UHE neutrons. We categorize them into twelve target sets: millisecond pulsars (msec PSRs) [4], gamma-ray pulsars (γ-ray PSRs) [5], low-mass X-ray binaries (LMXB) [6], high-mass X-ray binaries (HMXB) [7], TeV gamma-ray pulsars wind nebulae (TeV γ-ray - PWNe), other identified TeV gamma-ray sources (TeV γ-ray - other), unidentified TeV gamma-ray sources (TeV γ-ray - UNID)(1), microquasars(2), magnetars(3) [8], sources detected as PeVatrons by the Large High Altitude Air Shower Observatory (LHAASO) [9], and two single-element

(1) The PWNe, the other sources, and the unidentified sources were selected from `http://tevcat2.uchicago.edu/`.

(2) Chaty S., `http://www.aim.univ-paris7.fr/CHATY/Microquasars/microquasars.html`.

(3) `http://www.physics.mcgill.ca/ pulsar/magnetar/main.html`.

sets: the Galactic Center and the Crab. The field of view in the SD-750 dataset is reduced compared to the SD-1500 dataset. Additionally, the events in the SD-750 dataset have a lower energy range, between 0.1 and 1 EeV, which limits the potential search radius due to the neutron decay. To account for these constraints, we keep candidate sources with a maximum declination of $+20°$ and within a distance of 1 kpc when studying the SD-750 data set. Consequently, we examined 888 candidate sources using the SD-1500 dataset and 166 candidate sources using the SD-750 dataset.

4. – Method

To identify excesses around the direction of the candidate sources, we compare the observed cosmic ray (CR) density with the expected from the background. Using the scrambling technique, we estimate the background by producing isotropic arrival direction distributions, erasing small-scale anisotropies. We estimate the CR density at the direction of a target through the probability density of each event in the data set coming from the direction of the target. The probability density of a cosmic ray event coming from the direction of a target is given by [10]

$$w = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\xi^2}{2\sigma^2}\right), \tag{1}$$

where ξ is the angular distance between the event and the target and σ is the angular uncertainty of each event. We parameterize the angular uncertainty in multiplicity (number of triggered WCDs during the event) and zenith angle. To estimate the CR density at the direction of the target, we sum the weights w over the N events in the data set.

We compare the observed density with those obtained from scrambled data sets. To simulate an event, we sample two events from the observed data set, extracting from one information about the arrival time and from the other the zenith angle and angular uncertainty. Then, we sample an azimuth angle from a uniform distribution between 0 and 2π. We build data sets with the same number of events as the observed ones. To estimate the background, we simulate 10,000 scrambled data sets([4]).

The p-value is the fraction of scrambled data sets where the CR density exceeds the observed value. To account for the multiple trials in each target set, we penalize the p-values by the number of targets, M, as described in [2]. We penalize using $p^* = 1-(1-p)^M$, which reflects the probability of getting a p-value smaller or equal to p by chance, assuming the M p-values are sampled from a uniform distribution.

The upper limit on the number of neutrons is determined as the smallest value of n added events that satisfies the condition $f_n < (1-CL)f_0$, where f_0 represents the fraction of data sets in which the CR density at the target position is less than the observed density, f_n denotes this fraction after adding n events, and CL is the confidence level. For this analysis, we use a confidence level of 95%. The upper limit on the neutron flux is determined by dividing the upper limit on the number of neutrons by the directional exposure. The directional exposure is estimated by dividing the expected density by the

([4]) For the specific case of the gamma-ray pulsar located at $(296.6°, -54.1°)$, we simulated 200,000 data sets to estimate the p-value.

TABLE I. – *Results for the most significant target in each target set using the SD-750 data set, considering events above* 0.1 EeV.

Class	R.A. [deg.]	Dec. [deg.]	Flux U.L. [$\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$]	E-flux U.L. [$\mathrm{eV\,cm}^{-2}\,\mathrm{s}^{-1}$]	p	p^*
msec PSRs	140.5	−52.0	1.7	12.5	0.043	0.66
γ-ray PSRs	288.4	10.3	5.3	38.9	0.0056	0.47
HMXB	116.9	−53.3	2.1	15.1	0.0092	0.071
TeV γ-ray - PWN	277.9	−9.9	1.8	13.4	0.12	0.48
TeV γ-ray - other	288.2	10.2	5.5	40.2	0.0033	0.036
Magnetars	274.7	−16.0	1.6	11.8	0.13	0.44

CR intensity. The expected density is the average obtained from 10,000 scrambled data sets. The CR intensity is estimated by integrating the spectral shape described in [11]. Additionally, we estimate the upper limit on the energy flux, assuming an E^{-2} spectrum.

We conduct a "stacked analysis" to evaluate the probability that the classes of astrophysical objects are neutron emitters. The hypothesis is that if the candidate sources within a set emit neutrons, the combined signal should exhibit a greater significance than the individual targets. The probability that a set of M p-values, randomly sampled from a uniform distribution between 0 and 1, yields a product Π less or equal to the actual product of p-values, Π_0, is given by

$$\mathcal{P}(\Pi \leq \Pi_0) = \Pi_0 \sum_{k=0}^{M-1} \frac{(-\ln \Pi_0)^k}{k!} = 1 - \mathrm{Poisson}(M, -\ln \Pi_0), \tag{2}$$

where $\mathrm{Poisson}(\kappa, \mu)$ represents the probability of getting κ or more events in the presence of a background following a Poisson distribution with mean μ. We also evaluate the combined p-value including statistical weights. The weights are proportional to the

TABLE II. – *Results for the most significant target in each target set using the SD-1500 data set, considering events with energy above* 1 EeV.

Class	R.A. [deg.]	Dec. [deg.]	Flux U.L. [$\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$]	E-flux U.L. [$\mathrm{eV\,cm}^{-2}\,\mathrm{s}^{-1}$]	p	p^*
msec PSRs	286.2	2.1	0.026	0.19	0.0075	0.88
γ-ray PSRs	296.6	−54.1	0.023	0.17	5.0×10^{-5}	0.013
LMXB	237.0	−62.6	0.017	0.12	0.0069	0.51
HMXB	308.1	41.0	0.13	0.97	0.014	0.57
TeV γ-ray - PWN	128.8	−45.6	0.016	0.12	0.0070	0.18
TeV γ-ray - other	128.8	−45.2	0.014	0.11	0.022	0.63
TeV γ-ray - UNID	305.0	40.8	0.15	1.1	0.0066	0.31
Microquasars	308.1	41.0	0.13	0.95	0.014	0.19
Magnetars	249.0	−47.6	0.011	0.079	0.15	0.99
LHAASO	292.3	17.8	0.038	0.28	0.024	0.20
Crab	83.6	22.0	0.020	0.15	0.71	0.71
Galactic Center	266.4	−29.0	0.0053	0.039	0.86	0.86

TABLE III. – *Results of the combined analysis for different energy ranges using the SD-750 data set. In the table,* ΔE_1 *refers to the energy range* $E \geq 0.1\,\mathrm{EeV}$, ΔE_2 *to* $0.1 \leq E/\mathrm{EeV} < 0.2$, ΔE_3 *to* $0.2 \leq E/\mathrm{EeV} < 0.3$, *and* ΔE_4 *to* $E \geq 0.3\,\mathrm{EeV}$.

Class	No.	Unweighted combined p-value				Weighted combined p-value			
		ΔE_1	ΔE_2	ΔE_3	ΔE_4	ΔE_1	ΔE_2	ΔE_3	ΔE_4
msec PSRs	25	0.82	0.41	0.90	0.67	0.58	0.48	0.95	0.15
γ-ray PSRs	113	0.53	0.70	0.29	0.38	0.93	0.94	0.85	0.14
HMXB	8	0.33	0.68	0.069	0.28	0.23	0.79	0.22	0.029
TeV γ-ray - PWN	5	0.43	0.72	0.12	0.36	0.83	0.96	0.73	0.11
TeV γ-ray - other	11	0.074	0.55	0.070	0.16	0.58	0.82	0.22	0.44
Magnetars	4	0.31	0.48	0.26	0.21	0.14	0.35	0.046	0.40

exposure of the Observatory in that location, to the electromagnetic flux of the target, and its expected flux attenuation factor due to neutron decay, considering the traveled distance. The statistical weights are proportional to these factors, and normalized in a way that the sum of all the weights in a target set is equal to 1. We follow the same procedure to evaluate the combined p-value as in [2].

5. – Results

We present the results for the most significant target in each target set in table I and II for the SD-750 and SD-1500 data sets, respectively. We show the angular direction of the target, the upper limit on the flux and energy flux, the p-value, and the penalized p-value. The most significant target is the one with the smallest individual p-value.

We show the results of the "stacked analysis" in tables III and IV for the SD-750 and SD-1500 data sets, respectively, for different energy ranges. We report the number M of targets in each set, and the combined p-values, both with and without including statistical weights.

TABLE IV. – *Results of the combined analysis for different energy ranges using the SD-1500 data set.*

Class	No.	Unweighted combined p-value				Weighted combined p-value			
		≥ 1 [EeV]	$1-2$ [EeV]	$2-3$ [EeV]	≥ 3 [EeV]	≥ 1 [EeV]	$1-2$ [EeV]	$2-3$ [EeV]	≥ 3 [EeV]
msec PSRs	283	0.90	0.79	0.20	1.0	0.50	0.82	0.0093	0.81
γ-ray PSRs	261	0.16	0.12	0.50	0.86	0.020	0.0068	0.31	0.61
LMXB	102	0.62	0.89	0.11	0.55	0.25	0.79	0.44	0.067
HMXB	60	0.49	0.46	0.28	0.85	0.34	0.25	0.66	0.42
TeV γ-ray - PWN	28	0.24	0.52	0.072	0.49	0.0052	0.0072	0.035	0.51
TeV γ-ray - other	45	0.52	0.81	0.15	0.34	0.22	0.55	0.30	0.15
TeV γ-ray - UNID	56	0.61	0.85	0.57	0.40	0.75	0.94	0.67	0.23
Microquasars	15	0.39	0.49	0.50	0.68	0.81	0.85	0.75	0.38
Magnetars	27	0.99	0.99	0.85	0.67	0.98	0.95	0.78	0.90
LHAASO	9	0.22	0.31	0.54	0.31	0.42	0.60	0.43	0.35
Crab	1	0.71	0.54	0.30	0.93	···	···	···	···
Galactic Center	1	0.86	0.78	0.72	0.67	···	···	···	···

6. – Discussion and conclusions

Our study did not find clear evidence of neutron flux from any tested candidate sources across the examined energy ranges, reinforcing the findings previously reported by the Auger Collaboration. These results, however, do not rule out the presence of EeV neutrons from some Galactic sources if their flux levels at Earth are below our established upper limits. Additionally, our time-averaged upper limits apply to steady sources and do not constrain short-duration outbursts. In future works, we aim to investigate potential correlations with transient high-energy photon emissions from Galactic sources recorded by other observatories. We also plan to conduct an updated blind search for neutron flux in an upcoming work.

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