PROCEEDINGS OF SCIENCE

Search for neutrons from Galactic sources with the Pierre Auger Observatory

PoS(UHECR2024)103

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Astrophysical neutral particles, such as neutrons, are produced through interactions of charged cosmic rays in the vicinity of their acceleration sites and are not deflected by magnetic fields during propagation. Therefore, they can be traced back to their sources. Despite being unstable particles, neutrons can travel approximately 9.2 kpc per EeV of energy before decaying, confining the search for their possible sources to the Milky Way. In this study, which was carried out with 19 years of data collected by the Pierre Auger Observatory, we analysed data sets nearly three times larger than those used in previous analyses. We extended the search to declinations up to +45° and to lower energy showers by including data sets with reconstructed primary energies down to 0.1 EeV. This extensive, high-quality dataset is studied in correlation with catalogues of over 800 Galactic candidate sources, including the Crab Nebula, which is studied for the first time in this type of analysis. The analysis method we present has been specifically developed for this study, allowing us to establish upper limits on the neutron flux from the sources under investigation.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

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1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) remains one of the long-standing open questions in astroparticle physics [1]. This is partly due to the lack of knowledge of the extragalactic and galactic magnetic fields, which bend the trajectory of UHECRs depending on their rigidity, and to the unknown primary rigidity. The latter, results from the uncertainties in modelling the macroscopic cascades of particles triggered by UHECRs. However, cosmic rays can interact with protons and photons near the extreme environments of their astrophysical sources, producing highly energetic neutral particles, such as photons, neutrinos and neutrons, which point directly to their source upon detection.

Although extensive air showers (EAS) triggered by photon and neutrino primaries are in principle distinguishable from the proton-induced ones [2, 3], the only way to detect neutron primaries is through over-densities in the cosmic ray flux at small scales, over an isotropic background due to the stochastic deflections of charged cosmic rays. As neutrons have a proper lifetime of $\tau_0 = (878.4 \pm 0.5)\,\mathrm{s}$ [4], their mean decay length increases with their energy E as $d \simeq 9.2\,\mathrm{kpc} \times (E\,/\,\mathrm{EeV})$, allowing the probing of Galactic sources of UHECRs. Therefore, measuring or placing limits on the neutron flux at the EeV scale constraints Galactic candidate sources, in particular, the Galactic centre, while probing the transition between the Galactic and Extragalactic components of the cosmic ray spectrum [5, 6].

In this work, we update previous searches for point sources of neutrons using data from the Pierre Auger Observatory [7] by including nine more years of data-taking and extending the zenith range to $0^\circ < \theta < 80^\circ$, hence covering the declination band $-90^\circ < \delta < 45^\circ$. This corresponds to an increase in exposure from 36,000 km^2 sr yr to 110,000 km^2 sr yr [8]. Additionally, we lowered the energy threshold of the search to $E_{\mathrm{th}} = 0.1\,\mathrm{EeV}$, for particular data sets. A full characterization of the data and target sets is provided in Sections 2 and 3, respectively, while the updated method is detailed in Section 4. As none of the candidate sources tested in this study reveals compelling evidence of neutron flux, we place corresponding upper limits in Section 5.

2. Data sets

The present contribution uses data from the Pierre Auger Observatory [9]. The Observatory is located in the Argentinian Pampa Amarilla, at an average latitude of 35.2° S and longitude of 69.2° W. It comprises an array of $1,660$ water-Cherenkov detectors (WCDs), known as the surface detector (SD) array, spreading over $3,000\ \mathrm{km}^2$, along with 27 fluorescence telescopes in 4 different sites overlooking the SD-array. The latter is known as the Fluorescence Detector (FD) and provides the energy scale of the Observatory.

The SD samples the shower front of EASs triggered by UHECRs, allowing the reconstruction of their zenith, θ, and azimuth, ϕ, angles from the start times of the signals measured by WCDs. Moreover, it permits the determination of the shower energy via the calibration of the normalization of the footprint of the shower to the FD energy scale. The SD-1500 designates the larger array of $3,000\ \mathrm{km}^2$ in which the WCDs are arranged on a triangular grid with a 1,500 m spacing. In turn, the SD-750 corresponds to a sub-array of $\simeq 24\,\mathrm{km}^2$ where detectors are spaced by 750 m.

The data recorded by the SD-1500 array, spanning from 1 January 2004 to 31 December 2022, includes both vertical events ($\theta < 60°$) and inclined events ($60° < \theta < 80°$). These events were reconstructed using different algorithms [10, 11], covering a declination range of $-90° < \delta < 45°$. The dataset consists of more than $2,500,000$ events, which we analyse in the following energy ranges: $1\,\text{EeV} \leq E < 2\,\text{EeV}$, $2\,\text{EeV} \leq E < 3\,\text{EeV}$, $E \geq 3\,\text{EeV}$, as well as in the cumulative range $E \geq 1\,\text{EeV}$.

The data recorded by the SD-750 array spans from 1 August 2008 to 21 December 2022, containing $\sim 1,500,000$ exclusively vertical events ($\theta < 55°$). The corresponding exposure is $408\,\text{km}^2\,\text{sr}\,\text{yr}$. Due to the decreased spacing of the WCDs and its smaller area, the SD-750 covers mostly the energy range $0.1\,\text{EeV} - 1\,\text{EeV}$, so the respective dataset was divided into energy bins an order of magnitude lower than those used for the SD-1500 data. To ensure high-quality reconstruction, all events included in the analysis require all six stations surrounding the one with the highest recorded signal to be active. Furthermore, periods of array instability have been omitted from the dataset.

3. Target sets

Since the production of neutrons can be accompanied by γ-ray production, we explore γ-ray sources as potential candidates for EeV neutron sources, using updated catalogues relative to the ones used in [7]. A total of 888 point sources were used in the analysis, including the Crab Nebula thanks to the inclusion of inclined events. The catalogues include millisecond pulsars [12], γ-ray pulsars [13], low-mass X-ray binaries [14], high-mass X-ray binaries [15], TeV γ-ray Pulsar Wind Nebulae, other identified TeV γ-ray sources, unidentified TeV γ-ray sources[1], microquasars[2], magnetars[3] [16], and sources detected by the LHAASO Observatory as PeVatrons [17]. The Galactic centre and the Crab were used as single targets.

Since the observable neutron horizon is smaller for the lower primary energies measured by the SD-750, we only consider sources within 1 kpc or less. Along with the stricter zenith cut, this reduces the number of source candidates to 122.

4. Method

4.1 Definition of the test statistic

To detect small-scale over-densities in the cosmic ray flux, we take for each event, j, with a measured direction $\mathbf{n}_j$, the probability of coming from a source at position $\mathbf{u}_i$. For a Gaussian point spread function, this probability, w_{ij}, is given by

$$w_{ij} = \frac{1}{2\pi\sigma_j^2} \exp\left\{-\frac{\xi_{ij}^2}{2\sigma_j}\right\}, \tag{1}$$

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

[2] `http://www.aim.univ-paris7.fr/CHATY/Microquasars/microquasars.html`

[3] `http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

where $\xi_{ij} = \mathrm{acos}\left(\mathbf{u}_i \cdot \mathbf{n}_j\right)$ is the angular separation between event j and source i and σ_j denotes the angular uncertainty in the reconstruction of event j. Since some well-reconstructed events exhibited unrealistically low angular uncertainties, the values of σ_j were regularized as detailed in [8].

For a source i and a dataset with N events, we define the test statistic ρ

$$\rho_i = \sum_{j=1}^{N} w_{ij}, \tag{2}$$

which denotes the integrated cosmic ray density. In the presence of neutron flux, the weights w_{ij} for the corresponding events would increase, leading to a larger value of ρ_i.

The distribution of ρ_i is parametrized for each target using $10,000$ realizations of N events coming from an isotropic cosmic rays flux. Each realization is achieved by sampling independently a time-stamp t and a pair of zenith and angular uncertainties, (θ, σ) from the observed dataset, and randomly assigning an azimuth ϕ sampled from a uniform distribution $[0, 2\pi[$. This procedure thoroughly eliminates small-scale anisotropies, while maintaining the directional exposure of the Observatory and the large-scale structure of the cosmic ray flux.

The significance of an observed value of ρ_{obs} is given by the fraction of isotropic samples for which $\rho > \rho_{\mathrm{obs}}$. If this fraction is zero, more scrambled samples are generated. The obtained p-values are then penalized by the number of targets, M, in each target set as $p^* = 1 - (1-p)^M$. That is, p^* is the probability of measuring at least 1 p-value smaller or equal to p in M independent trials and under the hypothesis of an isotropic flux for which p is uniformly distributed in $[0, 1]$.

4.2 Computation of the flux upper limit

To compute the flux upper limit for a given target, we need the upper limit on the number of signal events n_{UL}, and the directional exposure. The directional exposure is determined by averaging the cosmic ray density from $10,000$ isotropized simulations and dividing by the integrated cosmic ray spectrum [18] over the relevant energy range. To obtain n_{UL}, we sample n events from a two-dimensional Gaussian using the observed angular uncertainty distribution. The value of n is incremented by 1 until ρ obeys

$$\mathcal{P}(<\rho_{\mathrm{obs}} \mid \langle\rho\rangle + \rho_{\mathrm{UL}}) > (1 - \mathrm{CL})\mathcal{P}(<\rho_{\mathrm{obs}} \mid \langle\rho\rangle), \tag{3}$$

where the confidence level CL is set to 95%, $P(<\rho_{\mathrm{obs}} \mid \langle\rho\rangle)$ is the cumulative density function evaluated at ρ_{obs} under the null hypothesis and $P(<\rho_{\mathrm{obs}} \mid \langle\rho\rangle + \rho_{\mathrm{UL}})$ is the cumulative density function under the alternative hypothesis that there is a signal with n_{UL} events corresponding to a shift ρ_{UL} in $\langle\rho\rangle$. This upper limit definition is based on [19]. The energy flux upper limit is also computed assuming a power-law neutron spectrum of the form E^{-2}.

4.3 Combined significance

The p-values obtained for each source in a given catalogue can be combined to determine the overall significance of a catalogue. We define the product of the p-values for M sources as $\prod = \prod_{i=1}^{M} p_i$, which follows the distribution of the product of uniformly distributed random variables in $[0, 1]$ under the null hypothesis. That distribution is $f_\Pi(\Pi) = (-\ln \Pi)^{M-1}/(M-1)!$. Thus, the significance of an observed product Π_{obs} is

$$\mathcal{P}(\Pi < \Pi_{\text{obs}}) = \int_0^{\Pi_{\text{obs}}} f_\Pi(\Pi)\,\mathrm{d}\Pi = \Pi_{\text{obs}} \sum_{k=0}^{M-1} \frac{(-\ln \Pi_{\text{obs}})^k}{k!} = 1 - \text{Poisson}(M, -\ln \Pi_{\text{obs}}), \quad (4)$$

where $\text{Poisson}(M, -\ln \Pi_{\text{obs}})$ is the probability of measuring at least M if M is sampled from a Poisson distribution with mean value $-\ln \Pi_{\text{obs}}$.

We also compute a weighted product of p-values, Π^ω, with weights proportional to the exposure of the Observatory at the source location, the measured electromagnetic flux, and the expected neutron decay flux attenuation based on the distance to the source. If this distance is unknown, this factor is omitted. The weights are normalized to 1 for each target set. The distribution of Π^ω is obtained from 10,000 isotropized event samples, and the combined p-value is given by the fraction of samples with $\Pi^\omega < \Pi^\omega_{\text{obs}}$.

5. Results

The pre-trial and penalized p-values for the most significant targets in each catalogue, along with the flux and energy flux upper limits are displayed in Tables 1 and 2, for the SD-1500 and SD-750 data sets, respectively. No significant candidate sources were identified. The most significant target corresponds to the γ-ray pulsar J1946-5403 located at (296.6°, −54.1°), in equatorial coordinates.

Table 1: Results for the most significant target in each source class, using the SD-1500 data with $E \geq 1$ EeV.

Class	R.A. [deg]	Dec. [deg]	Flux U.L. [km^{-2} yr^{-1}]	E-Flux U.L. [eV km^{-2} yr^{-1}]	p-value	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

Moreover, the results of the combined analysis can be found in Tables 3 and 4, for the SD-1500 dataset, and in Tables 5 and 6, for the SD-750 dataset. The combined p-values for each source class are, once more, not significant, for either dataset.

Table 2: Results for the most significant target in each source class, using the SD-750 data with $E \geq 0.1$ EeV.

Class	R.A. [deg]	Dec. [deg]	Flux U.L. [$\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$]	E-Flux U.L. [$\mathrm{eV\,km}^{-2}\,\mathrm{yr}^{-1}$]	p-value	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

Table 3: Results for the combined analysis for SD-1500 dataset.

Class	No.	Unweighted combined p-value P			
		≥ 1 EeV	$1-2$ EeV	$2-3$ EeV	≥ 3 EeV
msec PSRs	283	0.90	0.79	0.20	1.0
γ-ray PSRs	261	0.16	0.12	0.50	0.86
LMXB	102	0.62	0.89	0.11	0.55
HMXB	60	0.49	0.46	0.28	0.85
TeV γ-ray - PWN	28	0.24	0.52	0.072	0.49
TeV γ-ray - other	45	0.52	0.81	0.15	0.34
TeV γ-ray - UNID	56	0.61	0.85	0.57	0.40
Microquasars	15	0.39	0.49	0.50	0.68
Magnetars	27	0.99	0.99	0.85	0.67
LHAASO	9	0.22	0.31	0.54	0.31
Crab	1	0.71	0.54	0.30	0.93
Galactic Center	1	0.86	0.78	0.72	0.67

Table 4: Results for the combined analysis using statistical weights for SD-1500 dataset.

Class	No.	Weighted combined p-value P_ω			
		≥ 1 EeV	$1-2$ EeV	$2-3$ EeV	≥ 3 EeV
msec PSRs	283	0.50	0.82	0.0093	0.81
γ-ray PSRs	261	0.020	0.0068	0.31	0.61
LMXB	102	0.25	0.79	0.44	0.067
HMXB	60	0.34	0.25	0.66	0.42
TeV γ-ray - PWN	28	0.0052	0.0072	0.035	0.51
TeV γ-ray - other	45	0.22	0.55	0.30	0.15
TeV γ-ray - UNID	56	0.75	0.94	0.67	0.23
Microquasars	15	0.81	0.85	0.75	0.38
Magnetars	27	0.98	0.95	0.78	0.90
LHAASO	9	0.42	0.60	0.43	0.35

Table 5: Results for the combined analysis for SD-750 dataset.

Class	No.	Unweighted combined p-value P			
		≥ 0.1 EeV	$0.1 - 0.2$ EeV	$0.2 - 0.3$ EeV	≥ 0.3 EeV
msec PSRs	25	0.82	0.41	0.90	0.67
γ-ray PSRs	113	0.53	0.70	0.29	0.38
HMXB	8	0.33	0.68	0.069	0.28
TeV γ-ray - PWN	5	0.43	0.72	0.12	0.36
TeV γ-ray - other	11	0.074	0.55	0.070	0.16
Magnetars	4	0.31	0.48	0.26	0.21

Table 6: Results for the combined analysis using statistical weights for SD-750 dataset.

Class	No.	Weighted combined p-value P_ω			
		≥ 0.1 EeV	$0.1 - 0.2$ EeV	$0.2 - 0.3$ EeV	≥ 0.3 EeV
msec PSRs	25	0.58	0.48	0.95	0.15
γ-ray PSRs	113	0.93	0.94	0.85	0.14
HMXB	8	0.23	0.79	0.22	0.029
TeV γ-ray - PWN	5	0.83	0.96	0.73	0.11
TeV γ-ray - other	11	0.58	0.82	0.22	0.44
Magnetars	4	0.14	0.35	0.046	0.40

6. Conclusions

In this work, we reported the search for small-scale overdensities in the cosmic ray flux due to neutron emissions in the direction of Galactic candidate sources of UHECRs. None of the candidate sources tested in this study revealed compelling evidence for fluxes of EeV neutrons. So, we placed the most stringent direct upper limits on their hadronic emissions above 100 PeV. Moreover, neither of the weighted products of the p-values over the candidate sources of each catalogue was significantly low. Therefore, none of the source classes showed evidence of a neutron flux. In the future, we plan on verifying whether the excess of events coming from pulsar J1946-5403 is present below 1 EeV. Moreover, we plan on performing a blind search for neutron emissions on the whole sky and a search for a diffuse emission on the Galactic Plane.

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