Observation of the galactic PeVatron candidate LHAASO J2108+5157 with the Large-Sized Telescope for Cherenkov Telescope Array

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cherenkov telescope array

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Abstract

The Cherenkov Telescope Array (CTA) Observatory will be the next generation ground-based very-high-energy gamma-ray observatory, sensitive from 20 GeV up to 300 TeV. The Large-Sized Telescope prototype (LST-1), currently in the commissioning phase, was inaugurated in October 2018 on La Palma (Spain). It is the first of four LST telescopes for CTA, to be built on La Palma. In 2021, LST-1 performed observations of one of the Galactic PeVatron candidates, LHAASO J2108+5157, recently discovered by the LHAASO collaboration. We present results of our analysis of the LST-1 data, putting strong constraints on the emission of the source in the multi-TeV band. We also present results of multi-wavelength modelling using 12-years Fermi-LAT data and Target of Opportunity observations with XMM-Newton. We test different scenarios for the parent particles producing the high energy emission and put constraints on their spectra.

1. Introduction

Cosmic rays (CRs) with energies up to the knee ($E < 1$ PeV) are believed to be produced in cosmic accelerators, the so called PeVatrons, located in our Galaxy. Despite a substantial observational efforts in the last decades the origin of CRs and nature of PeVatrons remains unknown.

LHAASO J2108+5157 is the first gamma-ray source directly discovered in the Ultra-High-Energy (UHE) band (Cao et al. 2021). The source is reported to be point-like with 95% confidence level upper limit (UL) on its extension of 0.26°. There is no Very-High-Energy or X-ray counterpart to the source, but Cao et al. (2021) identified a close High-Energy (HE) soft point source 4FGL J2108.0+5155 at angular distance of 0.13°. There are two molecular clouds in the direction coincident with LHAASO J2108+5157, which would support the hypothesis of hadronic origin of the emission, if CR protons collide with the ambient gas and emit gamma rays via π^0 decay. Leptonic emission, however, cannot be excluded as UHE gamma-ray photons can be produced via Inverse-Compton (IC) scattering of relativistic electrons on low energy photon field, or via bremsstrahlung when colliding with atomic nuclei of ambient matter.

XMM-Newton

Target of Opportunity XMM-Newton observation was carried out on June 11, 2021 for a total of 13.6 ks. From the clean event files, we extracted images in the soft (0.5-2 keV) and hard (2-7 keV) bands. No significant X-ray emission (except for a soft spectrum X-ray binary) found in the FoV, which puts strong constraints on possible synchrotron emission of relativistic electrons. Unabsorbed and absorbed ULs are in the range 10^{-15} - 10^{-13} erg/cm^2/s, depending on the assumed source size and spectrum.

2. Observation and data analysis

LST-1

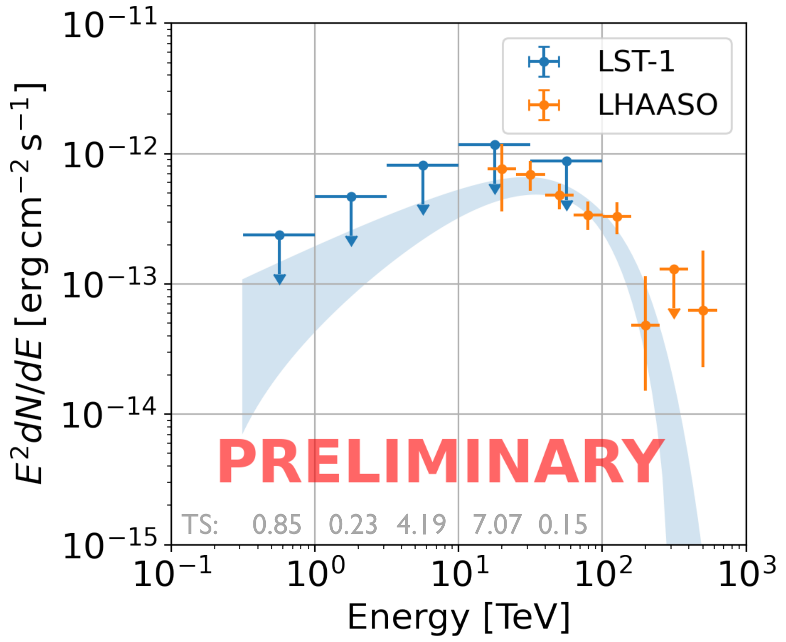
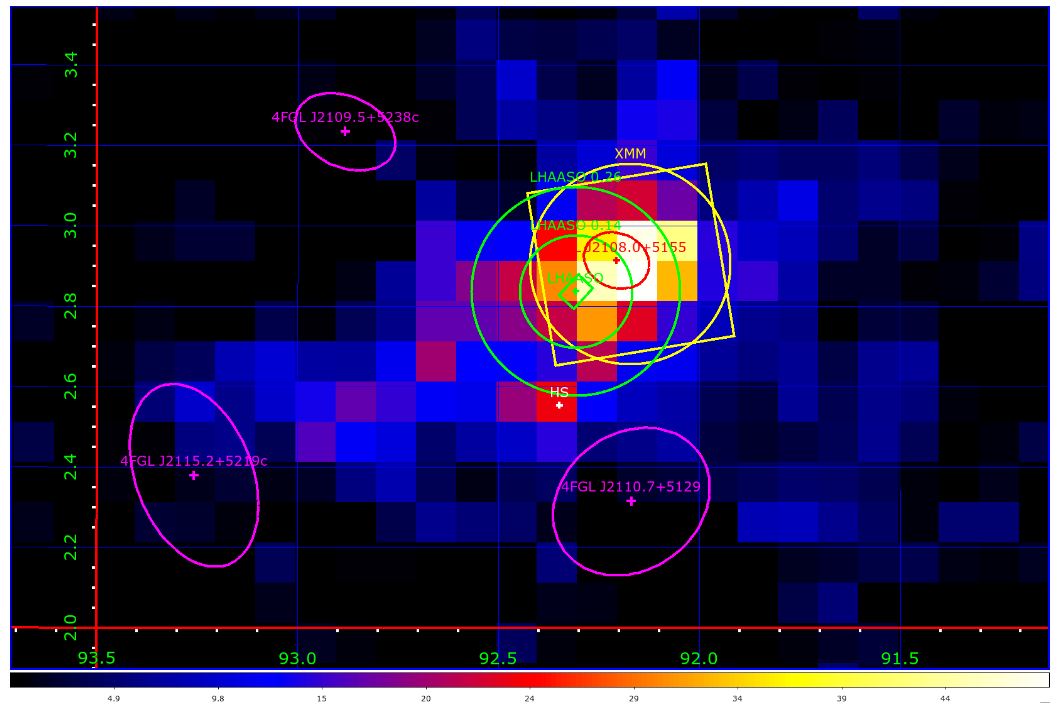


Figure 1: Spectral energy distribution of LHAASO J2108+5157. Butterfly plot represents best fitting spectral model and its statistical uncertainty. TS in individual LST-1 energy bins are reported in the figure. Orange flux points are taken from Cao et al. (2021).

LHAASO J2108+5157 was observed with LST-1 (Mazin et al. 2021) for 91 hours during 49 nights from June to September 2021. Quality cuts based on a stability of trigger rate, atmospheric transmission, rate of CR events and standard deviation of muon ring width were applied, resulting in 49.3 hours of good quality data. The data calibration and shower reconstruction was carried out using standard pipeline implemented in lstchain v0.9.6. We found a hint of hard point-like emission at $E > 3$ TeV, with a significance of 3.7σ. 1D spectral analysis was performed with the use of the gammapy package (Deil et al. 2017) in the energy range between 100 GeV and 100 TeV. To estimate source flux in individual energy bins, we run a joint likelihood fit of the LST-1 stacked dataset and LHAASO flux-points under the point-like source assumption, considering spectral shape in a form of power-law with exponential cutoff.



Fermi-LAT

We performed a dedicated binned analysis of the region with the publicly available Fermi-LAT science tool, analysing 12-year data. We show a hint of a potential hard source in Fermi-LAT data with a significance of 4σ which is not spatially correlated with LHAASO J2108+5157, but including it in the background model we were able to fine tune spectral representation of the HE counterpart 4FGL J2108.0+5155.

Figure 2: Fermi-LAT TS map. Sources present in the 4FGL-DR3 catalogue are shown (magenta and red ellipses). Green rectangle indicates the position of the LHAASO source with statistical uncertainty, while the smaller green circle represents 95% position uncertainty of 0.14°. The larger green circle indicate the 95% UL on the source extension of 0.26° (Cao et al. 2021). Yellow circle indicate XMM FoV and yellow square indicate the area covered with CCD detectors. White cross marks position of a new potential hard source.

3. Discussion of possible emission scenarios

Leptonic scenario

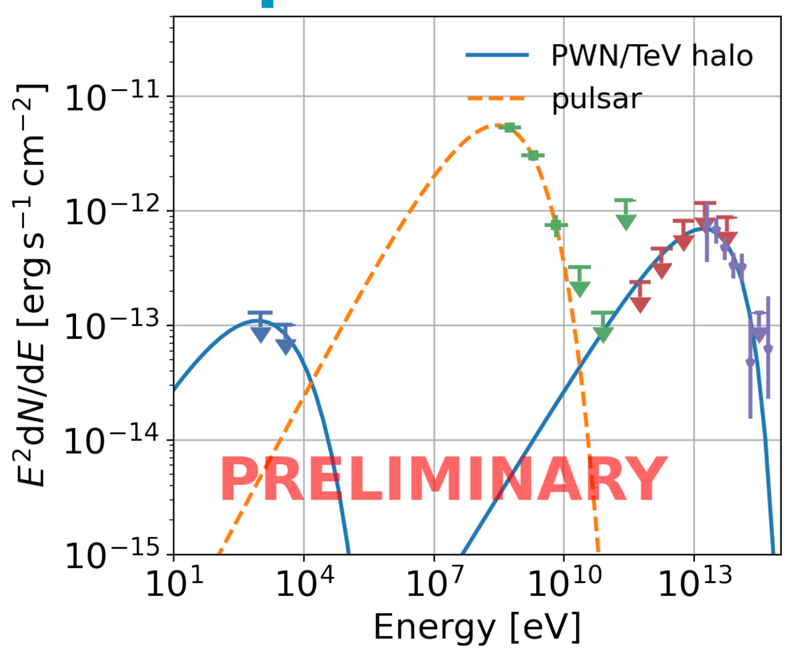


Figure 3: SED of LHAASO J2108+5157 showing leptonic scenario of emission. Data from different instruments are shown - LHAASO-KM2A (purple), XMM-Newton (blue), LST-1 (red), Fermi-LAT (green). The best fitting parameters of the UHE emission: sp. index of electrons $\alpha = 1.5^{+0.4}_{-0.5}$, E cutoff = 100^{+60}_{-30} TeV, B < ~1 uG.

We performed leptonic modelling of UHE emission in Naima package (Zabalza 2015), assuming exponential cutoff power law distribution of electrons interacting via IC with CMB and FIR. X-ray ULs strongly constrain magnetic field in the source - hard to explain in Pulsar Wind Nebula (PWN) scenario, but consistent with TeV halo hypothesis (Linden et al. 2017). Soft GeV emission of 4FGL J2108.0+5155 has spectral features compatible with a population radio quiet gamma-ray pulsars. We found that such tentative pulsar would release enough energy in the cooling time of relativistic electrons, to power UHE emission of the TeV halo. Possible source extension is also consistent with a size of typical TeV halo object, assuming Geminga-like diffusion coefficient (Sudoh et al. 2019). No pulsar associated with the UHE source, however, presents a challenge for the TeV halo scenario.

Hadronic scenario

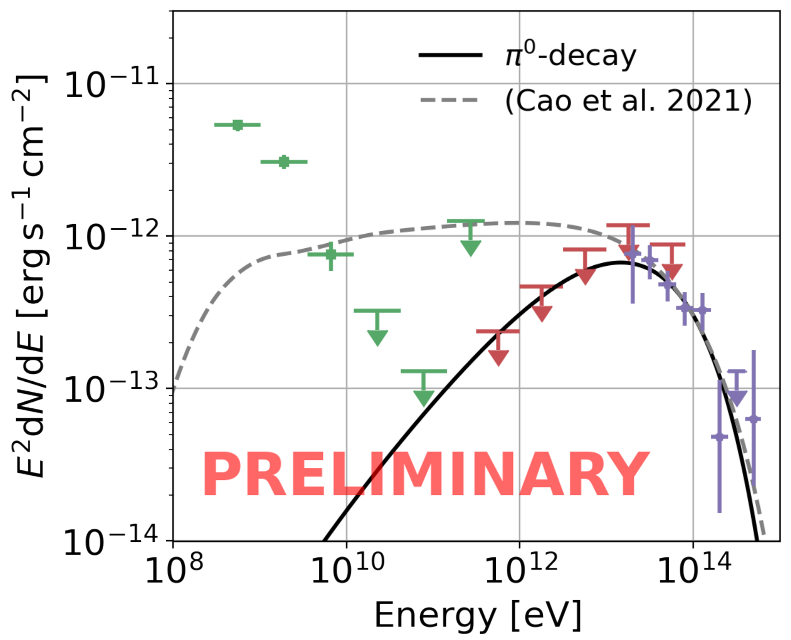


Figure 4: SED of LHAASO J2108+5157 with hadronic models of emission. The best fitting parameters of the UHE emission: sp. index of protons $\alpha = 0.8^{+0.5}_{-0.5}$, E cutoff = 250^{+200}_{-90} TeV. Grey dash-dotted line represents π^0 decay emission model with $\alpha = 2$ shown for reference (Cao et al. 2021).

We created a model of π^0 decay dominated UHE emission in Naima package, assuming proton distribution in form of exponential cutoff power law. While the total energy in relativistic protons is low enough ($E_{total} = 9 \times 10^{45}$ (d / 1 kpc)^2 (100 cm^{-3} / n) erg, where n is molecular density of one of the two molecular clouds with distance d in the direction to the source) compared to the typical energy of Supernova explosion, the required spectral index is too hard compared to the standard diffusive shock acceleration. The HE gamma-ray emission in hadronic scenario cannot be explained in a single component model together with UHE emission, and old SNR scenario seems to be unlikely due to very soft photon index of HE emission Γ = -3.2 (compare with Yuan et al. 2012).

References

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