PROCEEDINGS OF SCIENCE

Detection of Gamma-ray emission from W51 region with LHAASO

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The "π^0-decay bump" discovered in the gamma-ray spectra of some interacting supernova remnants (SNRs) is regarded as direct evidence for SNR acceleration of cosmic rays (CRs). However, the ability of SNRs to accelerate CRs to sub-PeV or even PeV energies remains a topic of ongoing debate. We report the LHAASO gamma-ray spectrum measurement of W51C, an interacting SNR exhibiting a π^0-decay bump. Owing to the unprecedentedly high sensitivity of LHAASO, we extend the gamma-ray spectrum to $\approx$ 200 TeV, an order of magnitude higher than the prior measurements. The results indicate a cutoff energy of $\approx$ 400 TeV for the incident proton spectrum, providing strong evidence that SNRs can serve as accelerators for sub-PeV CRs.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

*Speaker

1. Introduction

Supernova remnants (SNRs) have long been considered the dominant sources of Galactic cosmic rays (CRs). The "π^0-decay bump" discovered in the gamma-ray spectra of some interacting SNRs, that is, the SNRs that interact with the surrounding molecular clouds (MCs), can be regarded as direct evidence for SNR acceleration of CR nuclei [1]. However, the gamma-ray spectrum measurements of these interacting SNRs are limited below $\sim$ 10 TeV to date. Given that the energy of gamma-ray photons is about an order of magnitude less than that of the incident protons, it is still in the air whether SNR can accelerate CRs to energies above 100 TeV and dominate the CR spectrum below the "knee" ($\sim$ PeV).

W51C is one of such interacting SNRs with a significant π^0-decay bump [2]. The distance and age of W51C are estimated to be 5.5 kpc and 30 kyr, respectively. It is widely accepted that W51C interacts with the molecular cloud (MC) associated with the nearby star-forming region, W51B. This interaction is primarily evidenced by the 1720 MHz OH maser and the shocked gas discovered in the interaction zone [3]. Multiple experiments have detected gamma-ray emission in locations consistent with this interaction zone [4–8]. Here we report the joint measurement of the gamma-ray spectrum of W51C using both KM2A and WCDA, covering an energy range of $\approx 1 - 200$ TeV. This measurement notably extends the W51C gamma-ray spectrum towards high energy by one order of magnitude.

2. LHAASO observation

Large High Altitude Air Shower Observatory (LHAASO), a ground-based experiment located high on the edge of the Tibetan Plateau at an average altitude of 4410 meters, has broken through the limited energy of space-borne instruments and sensitively extended the measured energy go beyond sub-TeV to PeV. This hybrid array consists of Kilometer Square Array (KM2A), Water Cherenkov Detector Array (WCDA), and Wide Field of view Cherenkov Telescope Array (WFCTA). KM2A is highly sensitive to gamma rays above 25 TeV and serves as an influential sky survey tool for ultra-high-energy (UHE, $>$ 100 TeV) gamma-ray observation. The exceptional gamma/hadron discrimination capability allows for the precise determination of high-energy spectral characteristics of SNRs with unprecedented sensitivity. The WCDA, covering a vast area of 78,000 square meters, is sensitive to gamma rays within the sub-TeV to 25 TeV range. It primarily serves as a surveying tool for transient phenomena and the discovery of new TeV sources.

3. Data analysis

We conducted measurements with WCDA and KM2A in the W51C region for durations of 686 and 1124 days, respectively. These observations revealed an excess of gamma rays with statistical significances of 17.58σ, 18.37σ, and 5.96σ across three energy regimes of $<$ 25 TeV, $25 - 100$ TeV, and $>$ 100 TeV, respectively(see 1). To estimate the spatial and spectral distribution of W51C, we employed a conservative approach by fitting a relatively large region of interest (ROI) covering the entire W51 complex, as well as the ambient diffuse region. The flux morphology of Galactic diffuse emission (GDE) was assumed to follow the spatial distribution of Planck dust [9]. Moreover, we considered two significant spatially extended emissions from nearby sources, LHAASO J1919+1556 (1σ extent $\sigma_{\rm ext} = 0.21^\circ \pm 0.05^\circ$) and LHAASO J1924+1609 (1σ extent $\sigma_{\rm ext} = 1.22^\circ \pm 0.18^\circ$), by removing their contributions. We also attempted to detect the nearby PWN candidate, CXO J192318.5+140305, but its detection was hindered by the large angular resolution. The gamma-ray emission from W51C observed by both WCDA and KM2A were well-fitted using a symmetrical 2D Gaussian function, with centroids at $({\rm R.A.}, {\rm Dec})_{\rm WCDA} = (290.73^\circ \pm 0.02^\circ, 14.08^\circ \pm 0.02^\circ)$ and $({\rm R.A.}, {\rm Dec})_{\rm KM2A} = (290.73^\circ \pm 0.02^\circ, 14.10^\circ \pm 0.02^\circ)$, respectively. The extension of the gamma-ray emission from W51C for energies below 25 TeV was found to be $\simeq 0.17^\circ \pm 0.02^\circ$, while it was not significant for energies above 25 TeV, and we established an upper limit of 0.19° at a 95% confidence level. The measured extension is consistent with the findings of Fermi-LAT and MAGIC [6, 7].

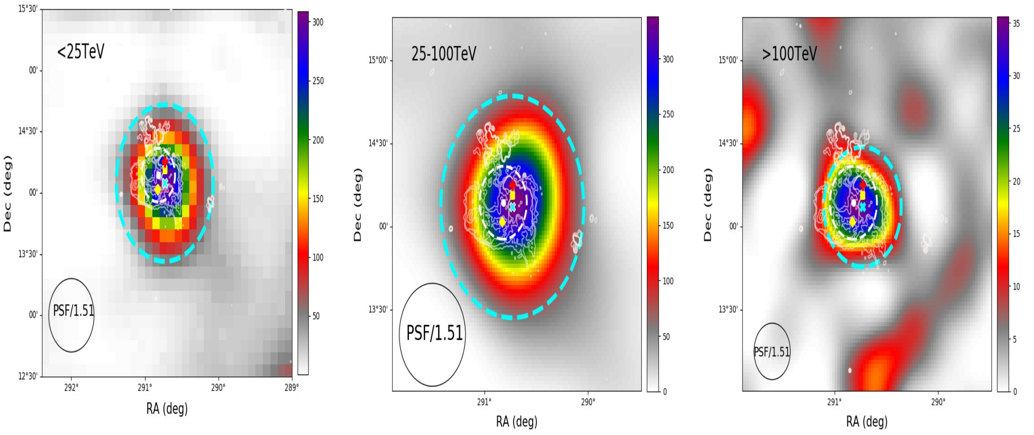

Figure 1: The VHE and UHE gamma-ray maps of W51 region in equatorial coordinate. The color scale indicates the statistical significance (square-root) of the excess gamma-ray counts after estimating the CR background. For energies below 25 TeV, 25 – 100 TeV, and above 100 TeV, the PSF values are 0.45°, 0.46° and 0.24°, respectively. The white contours represent the 21 cm radio continuum emission from VLA. The yellow diamond represents the position of the PWN candidate CXO J192318.5+140305, and the red cross indicates where 1720 MHz OH maser is emitted. The white dashed circle covers the systematic position error from Fermi-LAT, and the yellow square indicates the centroid position measured by MAGIC. The cyan cross and dashed cyan circle are the fitted position from LHAASO and 90% events coverage region, respectively.

The differential energy spectrum of gamma-ray emissions from W51C, spanning from 1 TeV to several hundred of TeV, is presented in Fig. xx. The spectrum below 25 TeV was accurately measured by WCDA and can be described by a single power law with an index of $\alpha \simeq 2.64 \pm 0.078$. The WCDA spectrum is consistent with the HAWC measurement [8], but approximately 1.6 times higher than the data from MAGIC[7]. The flux points from H.E.S.S. and Milagro also exhibit slight differences compared to the current measurements, but they remain statistically consistent with this study. Significantly, we have detected the highest energy gamma-ray emission from W51C, reaching up to 200 TeV with KM2A. The two closely aligned data points around 25 TeV from both WCDA and KM2A suggest a smooth connection in the overall spectrum. Moreover, through a joint fitting of the observed gamma-ray flux from 1 TeV to 200 TeV, we find a prominent cutoff at energies around $E_c = 56.13$ TeV. This cutoff is modeled by fitting a power-law function with an exponential cutoff, expressed as $dN_\gamma/dE = J_0(E/E_0)^{-\alpha}\exp(E/E_c)$.

4. Results and discussion

The gamma-ray energy spectra of WCDA and KM2A reported by the current work can be perfectly explained with a pure π^0-decay model. The energy spectrum of the incident protons is assumed to be a power law with an exponential cutoff, expressed by $dN_p/dE_p \propto E_p^{-\alpha}\exp(-E_p/E_{p,\mathrm{cut}})$, where E_p is the proton energy, and N_p is the proton number density. The best-fit spectral index is remarkably well-constrained at $\alpha \approx 2.58$. This spectrum is significantly softer than the one predicted by a strong shock (α = 2.0). The best-fit cutoff energy is found to be $E_{\rm cut} \approx 400$ TeV, which is substantially higher than the previously mentioned 100 TeV threshold.

The CRs illuminating the MC could either be carried by the current SNR shock (e.g., [10]) or escape during the early stages of the SNR (e.g., [11]). Both scenarios can naturally account for the observed soft spectrum. However, given the current shock speed of $\sim$ 300 km s^{-1}, the SNR is unlikely to accelerate fresh CR protons with energies higher than 100 TeV. SNRs may be capable of accelerating CR protons to ~PeV during their very early stages [12]. Assuming the presence of inefficient diffusion surrounding the SNR (e.g., induced by the escaping CRs themselves through streaming instability), plenty of high-energy CRs that escaped during the early stages could still be accumulated near the SNR and significantly illuminate the adjacent MC.

5. Summary

The gamma-ray emission from W51C is generally accepted to originate from hadronic processes, as supported by the π^0-decay bump in the gamma-ray spectrum and the compelling evidence of SNR-MC interaction. We present a joint measurement of the gamma-ray spectrum of W51C using both KM2A and WCDA, which spans an energy range of $\approx 1-200$ TeV. This finding provides strong support for the ability of SNRs to accelerate CRs to sub-PeV energies.

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