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Nuclear and electromagnetic cascades induced by ultrahigh-energy cosmic rays in radio galaxies: implications for Centaurus A

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The origin of ultrahigh-energy cosmic rays (UHECRs) is a long-standing mystery in astrophysics. Identifying the sources of these UHECRs, especially the nuclei component, is challenging and requires the detection of very-high-energy (VHE) gamma-rays ($\gtrsim$ 0.1 TeV) and neutrinos. In this study, we have developed a numerical code that considers both nuclear and electromagnetic cascades to solve the transport equation for UHECRs and their secondaries. We focus on Centaurus A, a nearby radio galaxy that is considered a promising candidate for UHECR acceleration. Building upon observations of extended VHE gamma-ray emission from its kiloparsec-scale jet by the H.E.S.S. telescope, we investigate the interactions between UHECRs accelerated in the large-scale jet and various target photon fields, including emission from the beamed core. Our analysis includes the photodisintegration and Bethe-Heitler pair-production processes, and we provide a comprehensive assessment of the VHE gamma-ray signatures from UHECR nuclei. Our results demonstrate the potential detectability of VHE gamma-rays from UHECR nuclei by ground-based gamma-ray telescopes, particularly if the dominant composition of UHECRs consists of intermediate-mass nuclei such as oxygen.

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1. Introduction

The origin of ultrahigh-energy cosmic rays (UHECRs) remains an unresolved problem in astrophysics. Observations indicating an increase in the fraction of heavier nuclei beyond approximately 4 EeV suggest that nearby sources dominate the highest energy range of UHECRs and are likely to accelerate heavier nuclei [e.g., 1].

In the era of multimessenger astrophysics, the detection of neutrinos and very-high-energy (VHE) gamma-rays (above 0.1 TeV) plays a crucial role in identifying UHECR accelerators. The hadronic components of VHE gamma-rays involve various processes, including electromagnetic cascades from photomeson production, hadronuclear interactions, Bethe-Heitler electron-positron production, and photodisintegration accompanied by de-excitation gamma-rays. The detection of de-excitation gamma-rays in the VHE range from nearby UHECR sources can provide direct evidence of the acceleration of heavier nuclei components of UHECRs. These de-excitation gamma-rays arise from the decay of excited nuclei transitioning from high-energy to low-energy states. For instance, photonuclear reactions triggered by lightning discharges can produce de-excitation gamma-rays in the MeV energy band [2].

Photodisintegration, particularly when the target photon energy in the nuclear rest frame exceeds the nuclear binding energy (around 10 MeV), plays a crucial role in determining the fate of UHECR nuclei. The resulting nuclear fragments are left in an excited state and rapidly de-excite by emitting one or several photons with energies around MeV in the nuclear rest frame. In the observer frame, these de-excitation gamma-rays are boosted to the VHE range for UHECR nuclei.

In this study, our aim is to investigate the influence of electromagnetic cascades on the multi-wavelength spectral energy distribution (SED) by considering the injection of UHECR nuclei. We utilize our code to model leptohadronic processes in the large-scale jet of Centaurus A (Cen A) and examine the detectability of de-excitation gamma-rays. Unlike previous work on blazars, we focus on the acceleration zone located in the large-scale jet, motivated by recent studies conducted by the H.E.S.S. Collaboration [5].

2. Methods

Fig. 1 illustrates the interactions of cosmic ray (CR) nuclei and electrons, showcasing the nuclear and electromagnetic cascades induced by CR nuclei within the large-scale jet of radio galaxies. The depicted physical processes encompass the photodisintegration of nuclei, photomeson production, Bethe-Heitler pair production, and the associated electromagnetic cascades.

In the context of large-scale relativistic jets, shear acceleration occurs when charged particles interact with magnetic field irregularities across different layers of the shearing flow [6]. As a result, the accelerated cosmic rays typically exhibit a power-law distribution with an exponential cutoff. The maximum attainable energy for accelerated UHECR nuclei can be estimated under the confinement limit. This is given by:

$$
\begin{aligned}
E_{\max} &\approx \frac{1}{\eta}\Gamma_{\rm kpc} ZeB\beta l_b \\
&\simeq 110(Z/26)\Gamma_{\rm kpc}\left(\frac{\eta}{7}\right)^{-1}\left(\frac{B}{10^{-4}\ \rm G}\right)\left(\frac{\beta}{0.3}\right)\left(\frac{l_b}{1\ \rm kpc}\right)\ \rm EeV, \qquad (1)
\end{aligned}
$$

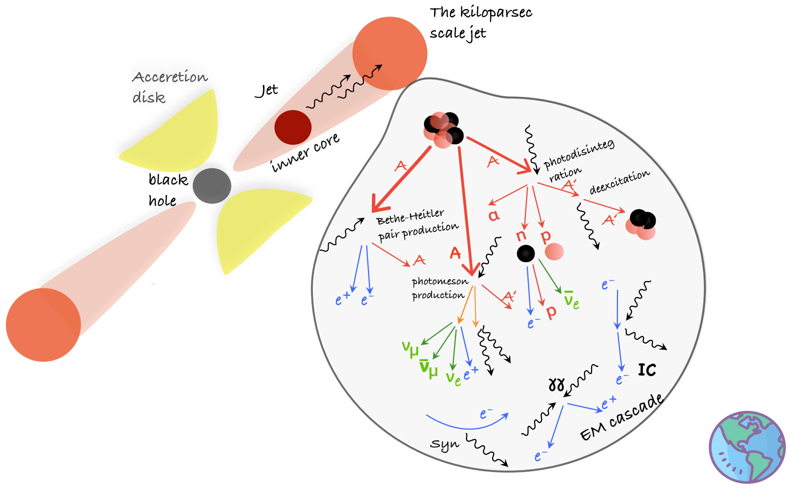

Figure 1: Schematic depiction of neutrino and gamma-ray production processes involving protons, nuclei, and electrons, including nuclear and electromagnetic cascades induced by CR nuclei in radio galaxies.

where η is a prefactor, typically a few in the Bohm limit, B represents the strength of the magnetic field, l_b denotes the comoving radius of the particle acceleration region, β is the velocity in units of the speed of light, and $\Gamma_{\rm kpc}$ is the Lorentz factor of the jet in kiloparsecs. The spectral index, denoted as $s_{\rm acc}$, can vary significantly depending on the flow speed. For non-relativistic flows, it may be much steeper, while trans-relativistic and relativistic flows generally exhibit harder spectral indices.

We consider the emission region as a spherical blob that is moving towards us at a speed below the speed of light. The main source of target photons in this scenario is the non-thermal broad-band emission originating from the inner core. The Doppler factors assigned to the inner core and the large-scale jet are $\Gamma_{\rm core} = 5$ and $\Gamma_{\rm kpc} = 1.05$, respectively. Our calculations rely on the Astrophysical Multimessenger Emission Simulator (AMES), which enables us to simultaneously model the nuclear cascade and the electromagnetic cascade by solving interconnected transport equations. The physical processes taken into account include the photodisintegration process, photomeson production process, Bethe-Heitler pair production process, and electromagnetic cascade.

3. Results

Our results are shown in Fig. 2. We consider a single component, either UHECR oxygen nuclei (upper panel) or UHECR iron nuclei (lower panel), for illustrative purposes. The solid blue and red curves represent the results from injecting primary electrons and UHECR nuclei, while the solid black lines represent the SED of the inner core. The green squares and red circles represent data points from the inner core, covering a range from low-energy radio to optical and high-energy X-ray to GeV bands. The cyan circles represent observed data points from the radio to X-ray band, corresponding to the total flux in the inner region of the large-scale jet [3]. The cyan triangles represent the total X-ray flux, including a larger region of the large-scale jet [4]. The cyan 'butterfly' represents the observed VHE γ-ray flux by H.E.S.S. [5]. Additionally, the figure displays the expected VHE γ-ray sensitivities of the Cherenkov Telescope Array (CTA) (50 hours, grey solid lines) [7], the Large High Altitude Air Shower Observatory (LHAASO) (1 yr, grey dashed lines) [9], and the Southern Wide-field γ-ray Observatory (SWGO) (5 yr, grey dotted lines) [8].

The predicted multi-wavelength SED from the injection of UHECR nuclei exhibits four distinct peaks. In the keV energy range, the dominant component is synchrotron emission from electron-positron pairs produced through the Bethe-Heitler pair production process. At the GeV energy range, synchrotron emission from electron-positron pairs produced through the photomeson production process dominates the flux. In the TeV energy range, the bump in the spectrum can be attributed to inverse Compton emission via electron-positron pairs produced from the Bethe-Heitler pair production process. At even higher energies around 100 TeV, the de-excitation gamma-rays resulting from the photodisintegration process of UHECR nuclei become significant. The uncertainty in the flux of de-excitation gamma-rays is indicated by the shaded area between two curves beyond approximately 10 TeV. The light-shaded region represents the spectrum without extra-background light (EBL) absorption, while the dark-shaded region accounts for EBL absorption. Our results suggest that despite strong EBL absorption, the detection of de-excitation gamma-rays by current and future ground-based VHE gamma-ray telescopes, such as CTA, SWGO, and LHAASO (included only for comparison, as Cen A is not in its field of view), is feasible.

4. Implications for UHECRs and neutrinos

The power of UHECR nuclei in the large-scale jet can be estimated using the equation: $L_{\rm inj}^{\rm UHECR} \approx 2\Omega_j \beta_{\rm kpc} c R^2 \Gamma_{\rm kpc}^2 u_{\rm inj}$. Here, $\Omega_j \approx \pi l_b^2/R^2$ is the opening solid-angle, R is the distance of the kiloparsec-scale jet to the inner core, and $u_{\rm inj}$ is the comoving frame UHECR injection energy density. For the injection of UHECR oxygen nuclei, the injection luminosity is approximately 7.2×10^{43} erg s^{-1}, while for iron nuclei component, it is around 2.4×10^{43} erg s^{-1}. The predicted flux of observed UHECRs on Earth is depicted in Fig. 3. We consider the confinement timescale of UHECR nuclei from the large-scale jet as the maximum between the diffusion escape timescale and the light crossing timescale $t_{\rm conf} \approx \max[t_{\rm diff}, t_{\rm lc}]$, where $t_{\rm diff} \approx l_b^2/6D$ is the diffusion escape timescale and $t_{\rm lc} = l_b/c$ is the light crossing time scale. For our analysis, we assume that the emission from Cen A has been continuous with a recent burst of activity lasting $t_{\rm act} = 1$ Myr. Our expected UHECR flux aligns with the observed results when considering an average intergalactic magnetic field strength of $B = 10^{-9}$ G and a typical coherence length of $l_{\rm coh} = 100$ kpc.

The energy spectrum of high-energy neutrinos resulting from pion decay and neutron β-decay during the photodisintegration process is shown as green lines in Fig. 3. The neutrino flux is prominent in the $\sim$ 10 PeV energy range, primarily due to the pion decay process. In the lower energy range of $\sim$ 0.01 PeV, the neutron β-decay process dominates the neutrino flux.

The detection of high-energy neutrino emission from Cen A can be pursued by upcoming neutrino telescopes, such as KM3Net and IceCube-Gen2. Since Cen A is located in the Southern sky, KM3Net exhibits higher sensitivity compared to IceCube-Gen2 for capturing high-energy neutrinos from this source. However, it should be noted that the predicted flux of high-energy neutrinos in this study is approximately one to two orders of magnitude smaller than the predictions

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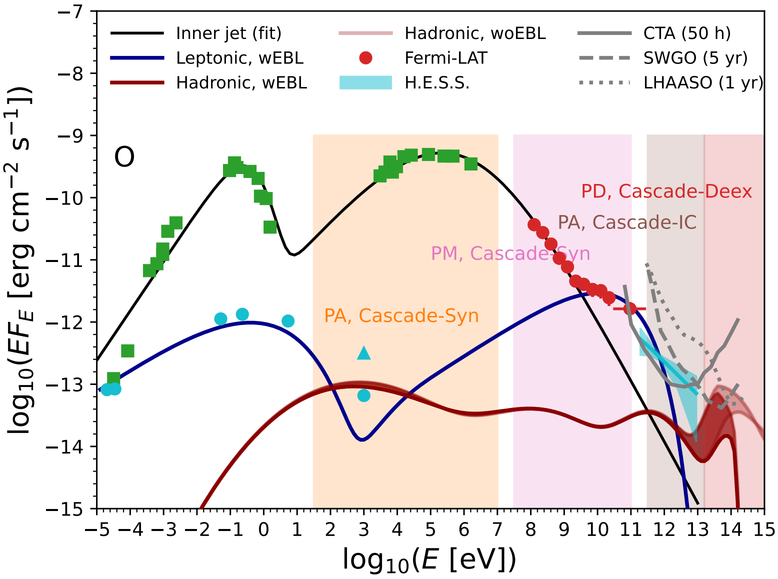

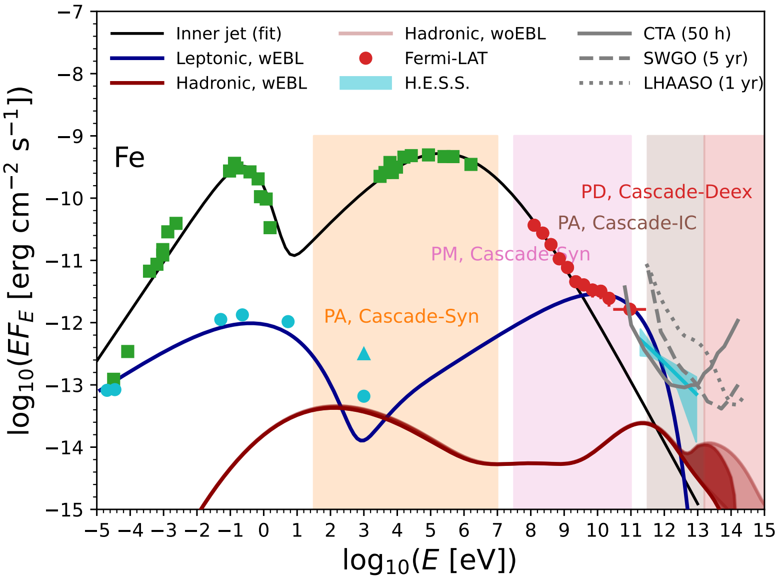

Figure 2: Predicted multi-wavelength spectral energy distribution (SED) from the kiloparsec-scale jet. The solid blue lines represent the SED after injecting primary high-energy electrons, while the solid red lines represent the SED after injecting UHECR nuclei. The solid black lines correspond to the SED of the inner core.

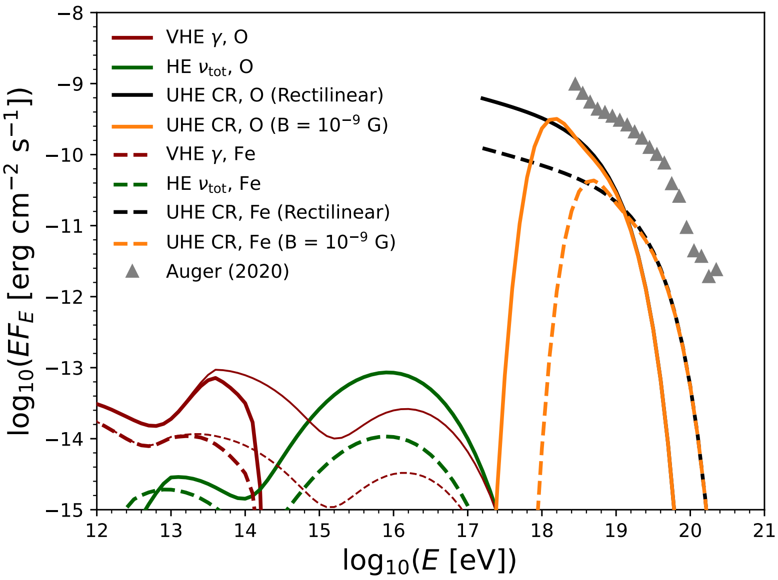

Figure 3: Predicted fluxes of high-energy γ-rays, neutrinos, and cosmic rays at Earth from Cen A's kiloparsec-scale jet. The solid lines represent the fluxes after injecting UHECR oxygen nuclei, while the dashed lines show the fluxes after injecting iron nuclei.

of the magnetically-powered corona model for Cen A, making the detection of high-energy neutrinos a challenging task.

5. Summary

In this study, we examined the detectability of de-excitation VHE γ-rays using our numerical code AMES, which accounts for both nuclear and electromagnetic cascades. Our findings, considering the injection of UHECR nuclei primarily composed of oxygen and/or iron, suggest that de-excitation VHE γ-rays will contribute significantly to the multi-wavelength spectrum at energies $\gtrsim 10 - 100$ TeV if the oxygen-group components dominate the UHECR nuclei. Current and future ground-based VHE γ-ray telescopes have the potential to detect these de-excitation VHE γ-rays from Cen A. The results obtained in this study offer valuable insights into the composition of UHECR nuclei in nearby extragalactic sources.

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