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Active Galactic Nuclei Jets Enriched by Wolf-Rayet Stars and Their Possible Contribution to Ultra-High-Energy Cosmic Rays

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Despite all that we have learned from observational data, the sources of ultra-high-energy cosmic rays (UHECRs) have not yet been identified. Among the candidates discussed in the literature, starburst galaxies and active galactic nuclei (AGNs) are likely the most popular. Studies from the Pierre Auger Observatory indicate that the mass composition of particles with energies above $10^{19.3}$ eV is compatible with Carbon-Nitrogen-Oxygen (CNO) nuclei. While starburst galaxies contain the necessary CNO elements, their energy budget has been shown to be insufficient to accelerate UHECRs beyond 1 EeV. In contrast, radiogalaxies, a subclass of AGNs, provide the required energy through their powerful jets. The lepton-dominated nature of these jets, however, makes the presence of nuclei nontrivial, requiring a mass-loading mechanism. One possible process for introducing nuclei into these jets is the interaction with embedded stars. In this work, we investigate the role of Wolf-Rayet (WRs) stars, which have CNO-rich winds, in supplying intermediate-mass nuclei to AGN jets. By exploring typical parameters for radiogalaxies, we estimate the resulting integrated UHECR flux and find solutions consistent with the flux measured by the Pierre Auger Observatory, suggesting that WR stars can supply sufficient CNO and heavier nuclei to be accelerated in AGN jets. We also discuss our results for the expected mass-composition fractions and the spectrum observed on Earth after propagation, particularly for Centaurus A.

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PoS(ICRC2025)343

1. Introduction

Active galactic nuclei (AGN) and their jets are promising candidates for the acceleration of ultra-high-energy cosmic rays (UHECRs). The observational studies by the Pierre Auger Collaboration have revealed indications of a possible correlation, though not yet statistically definitive, between the arrival directions of UHECRs and these energetic sources [1]. On the other hand, the composition of cosmic rays detected at energies above $10^{19.3}$ eV appears to be dominated by intermediate-mass nuclei, especially those within the Carbon-Nitrogen-Oxygen (CNO) group [2], suggesting that UHECRs likely originate from astrophysical environments enriched with these elements.

While starburst galaxies are well-known for their high abundance of CNO nuclei due to their intense star formation, their overall energy output is generally insufficient to accelerate cosmic rays to the highest energies observed [3]. This limitation is understood through the Hillas-Lovelace criterion, which places a constricting requirement on the kinetic power of sources needed to accelerate particles of a given charge up to a given energy [4].

In contrast, radiogalaxies, a subclass of AGN distinguished by their prominent and powerful radio jets, have kinetic energies ranging from 10^{42} up to 10^{48} erg s^{-1}, thus satisfying the energetic conditions to accelerate UHECRs [4]. Although these jets are thought to be predominantly composed of leptons, observations of jet deceleration suggest significant baryon loading occurs, likely as a consequence of interactions between the jets and stars embedded within or crossing the jet flow [5]. Previous studies have concentrated on red giant stars as sources of baryon entrainment, but these stars provide limited quantities of the CNO nuclei relevant to UHECR composition [6].

We investigate the potential contribution of Wolf-Rayet (WR) stars to the chemical enrichment of radiogalaxy jets. WR stars are massive evolved stars characterized by strong stellar winds with high mass-loss rates, rich in CNO nuclei, and element fractions that closely align with the composition inferred from UHECR observations [7]. We examine whether interactions between WR stars and AGN jets can effectively enhance the metallicity of the jets, thereby providing a source of intermediate-mass nuclei suitable for acceleration to ultra-high energies. Moreover, we explore the implications of this enrichment for a specific source, Centaurus A, by evaluating the contribution of our model to the total UHECR flux after propagation, in comparison with the observations reported by the Pierre Auger Observatory. Preliminary results from this study were previously presented in [8].

2. Model

Many young stars have been observed near the centers of the Milky Way and other galaxies. In our Galaxy, Wolf–Rayet (WR) stars are mostly found within a galactocentric radius of 500 pc along the Galactic plane and at vertical distances below 300 pc [9]. In radiogalaxies such as Centaurus A, detecting young stellar populations in the central regions is considerably more challenging. The intense emission from the AGN, combined with dust obscuration and the complex dynamics of the nuclear environment, often masks the signatures of young stars. Despite these difficulties, there is also growing evidence for the presence of young stellar populations in the central parts of several AGN host galaxies (see e.g., [10]).

PoS(ICRC2025)343

For this analysis, we assume the presence of a single WR star embedded within the jet. These stars have powerful stellar winds with typical mass-loss rates of $\dot{M}_{\rm WR} = 10^{-4}\, M_\odot\,{\rm yr}^{-1}$ and terminal velocity of $v_{\rm wind} = 3000\,{\rm km\,s^{-1}}$ [11]. The density of the stellar wind at a distance r from the star is described by [8, 12]

$$\rho_{\rm wind}(r) = \frac{\dot{M}_{\rm WR}}{4\pi r^2 v_{\rm wind}}. \tag{1}$$

Over its typical lifetime of $\tau \sim 5$ Myr, the WR star expels chemically enriched material composed primarily of helium and carbon. We adopt a wind composition model consistent with [7], in which the mass fraction λ_A of the element with mass number A is given by: $\lambda_4 = 0.6741$, $\lambda_{12} = 0.27$, $\lambda_{16} = 4.8\times10^{-2}$, $\lambda_{20} = 6.9\times10^{-3}$, $\lambda_{24} = 4.4\times10^{-4}$, $\lambda_{28} = 3.9\times10^{-4}$, $\lambda_{56} = 1.1\times10^{-4}$. These values correspond to helium, carbon, oxygen, neon, magnesium, silicon, and iron, respectively. This wind model does not contain hydrogen.

We adopt parameters representative of Centaurus A, the nearest and best-studied radiogalaxy, which also lies within the hotspot region reported by the Pierre Auger Observatory [1]. The jet is assumed to be conical, expanding with a half-opening angle $\theta = 5°$. At a distance z from its base, the jet radius and mass density follow [13]

$$R_{\rm jet}(z) = z\,\tan\theta, \qquad \rho_{\rm jet}(z) = \frac{L_{\rm jet}}{(\Gamma-1)\,c^3\,\pi\,R^2_{\rm jet}(z)} \propto z^{-2}, \tag{2}$$

respectively, where the jet power is $L_{\rm jet} = 10^{43}\,{\rm erg\,s^{-1}}$ and the bulk Lorentz factor is $\Gamma = 2$ [14].

When the jet interacts with the WR star, a double bow-shock structure forms, with the stagnation point located at

$$\frac{R_{\rm sp}(z)}{R_{\rm jet}(z)} = \sqrt{\frac{\dot{M}_{\rm WR} v_{\rm wind} c}{4L_{\rm jet}}} \approx 3.8\times10^{-2}\left(\frac{\dot{M}_{\rm WR}}{10^{-4}M_\odot{\rm yr}^{-1}}\right)^{\frac{1}{2}}\left(\frac{v_{\rm wind}}{3000\,{\rm km\,s^{-1}}}\right)^{\frac{1}{2}}\left(\frac{L_{\rm jet}}{10^{43}{\rm erg\,s^{-1}}}\right)^{-\frac{1}{2}}, \tag{3}$$

measured from the center of the star [8]. The interface between the shocked stellar wind and the shocked jet material is expected to be turbulent due to velocity shear (see Fig. 1, left panel). Kelvin-Helmholtz instabilities arise, facilitating mixing of the stellar wind into the jet flow [15]. Taking the instability length scale as $R_{\rm sp}(z)$, the Kelvin-Helmholtz timescale is

$$t_{\rm KH}(z) = \frac{2R_{\rm sp}(z)}{c}\sqrt{\frac{\rho_{\rm wind}(z)}{\rho_{\rm jet}(z)(\Gamma-1)}} \propto z, \tag{4}$$

whereas the time for the star to cross the jet is

$$t_{\rm cross}(z) = \frac{2R_{\rm jet}(z)}{v_{\rm K}(z)} \propto z^{3/2}, \tag{5}$$

with $v_{\rm K}(z)$ being the Keplerian velocity of the star. Assuming the mass of the central black hole is $M_{\rm BH} = 6\times10^7\,{\rm M}_\odot$ and the other parameters introduced before, the ratio

$$\frac{t_{\rm KH}(z)}{t_{\rm cross}(z)} = 7\times10^{-3}\left(\frac{z}{\rm pc}\right)^{-1/2} \tag{6}$$

indicates that instabilities develop well before the star exits the jet, enabling efficient mixing of wind material for distances $z > 5\times10^{-5}$ pc. The mixing rate is parameterized as $\dot{M}_{\rm mix} = \alpha\dot{M}_{\rm WR}$, with $\alpha \leq 1$.

3. Results

We consider the case when the wind material mixes completely into the jet, i.e., $\alpha = 1$ and $\dot{M}_{\rm mix} = \dot{M}_{\rm WR}$. Using the mass fractions $\lambda_{\rm A}$ introduced before, we calculate the injection rate of particles of each species into the jet as

$$\dot{\Phi}_{\rm A} = \lambda_{\rm A} \frac{\dot{M}_{\rm WR}}{m_{\rm A}}, \tag{7}$$

where $m_{\rm A}$ is the mass of element A. We further assume that a fraction $\xi \leq 1$ of these particles, characterized by mass number A and atomic number $Z_{\rm A}$, are accelerated to a power-law energy spectrum with an exponential cutoff [16]

$$\frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E} = \kappa_{\rm A} E^{-p} e^{-E/E_{\rm A}^{\rm max}}, \quad \text{for } m_{\rm A}c^2 < E < E_{\rm A}^{\rm max} = 6 \times 10^{18} Z_{\rm A}\ {\rm eV}, \tag{8}$$

where the constants $\kappa_{\rm A}$ are fixed by

$$\xi\, \dot{\Phi}_{\rm A} = \int_{m_{\rm A}c^2}^{E_{\rm A}^{\rm max}} \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\, {\rm d}E. \tag{9}$$

In this study, we do not specify a particular acceleration mechanism. Therefore, the spectral index p is treated as a free parameter, varied between 1 and 2.7 to cover a broad range of theoretical acceleration scenarios.

Since the total power available for particle acceleration is limited by the jet luminosity $L_{\rm jet}$,

$$\epsilon\, L_{\rm jet} = \sum_{\rm A} \int_{m_{\rm A}c^2}^{E_{\rm A}^{\rm max}} E \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\, {\rm d}E \tag{10}$$

with $\epsilon \leq 1$. For this study, we assume that $\epsilon = 0.3$, i.e., 30% of the jet power is allocated for particle acceleration. Combining Eq. 9 and Eq. 10, we find that the maximum fractions of accelerated particles ξ, constrained by the jet power, vary between 3.44×10^{-9} and 0.27 for spectral indices in the range $1 \leq p \leq 2.7$, respectively. This indicates that, for a single star, only a small fraction of the particles entrained via wind mixing could be accelerated if the spectrum is hard ($p = 1$), whereas up to 27% could be accelerated for softer spectra ($p = 2.7$). Consequently, adding more stars to the jet does not necessarily increase the predicted flux in our model unless either the jet power is higher or the number of particles entrained from a single star is smaller than the number allowed by Eq. 10.

Recent results from the Pierre Auger Collaboration suggest that UHECRs with energies between $10^{19.3}$ eV and $10^{20.2}$ eV are dominated by CNO nuclei [2]. The expected integrated UHECR flux from our model for a source at distance D is given by

$$J_{\rm UHECR}^{\rm source}(> 10^{19.3}\ {\rm eV}) = \frac{1}{4\pi D^2} \sum_{A \geq 4} \int_{10^{19.3}\ {\rm eV}}^{10^{20.2}\ {\rm eV}} \xi E \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\, {\rm d}E, \tag{11}$$

which we compare with the integrated flux measured by Auger, $J_{\rm Auger}(> 10^{19.3}\ {\rm eV}) = 8.4 \times 10^{37}\ {\rm erg\, Mpc^{-2}\, s^{-1}\, sr^{-1}}$ [17]. The right panel of Fig. 1 shows the ratio $J_{\rm UHECR}^{\rm source}/J_{\rm Auger}$ for $\epsilon = 0.3$

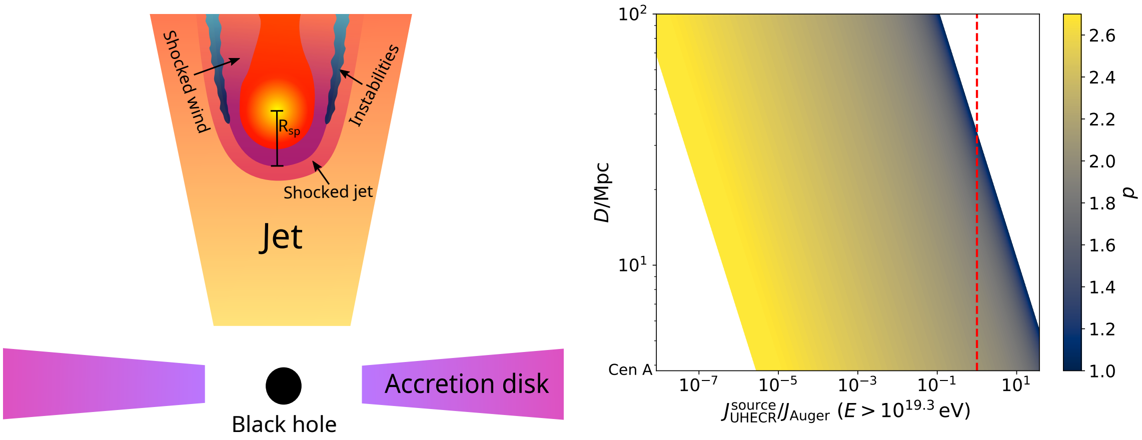

Figure 1: *Left panel*: Sketch of the physical situation (not to scale). *Right panel*: Fraction of the integrated flux above $10^{19.3}$ eV produced by one WR star for various spectral indices p and distances D. Results assume a jet power of $L_{\rm jet} = 10^{43}\,{\rm erg\,s^{-1}}$ and a fraction $\epsilon = 0.3$ of the jet power going into the acceleration of particles. The red line marks the position corresponding to 1 on the x-axis.

as a function of distance D from 3.8 to 100 Mpc, where 3.8 Mpc corresponds to the distance to Centaurus A [14]. Our results indicate that, for a source at Centaurus A distance, the predicted flux without accounting for propagation effects matches or exceeds the Auger flux when the spectral index satisfies $p \leq 2$.

In order to compute the effect of propagation, we perform one-dimensional simulations using `CRPropa 3.2` [18], including particle interactions with both the cosmic microwave background and the extragalactic background light, adopting the latter from the model by [19]. The following physical processes are included in our simulations: photo-disintegration, photo-pion production, electron–positron pair production, nuclear decay, and cosmological redshift, the last of which has a negligible effect at the distance of Centaurus A. For each particle type, 100,000 particles were simulated.

Figure 2 shows the result for particle distributions with spectral index $p = 2$ at the source, the cutoff energies given by Eq. 8, and the normalization factors from Eq. 10. We find that, although our model reproduces the energy spectrum observed at Earth by the Pierre Auger Collaboration reasonably well in both shape and mass composition between 6×10^{18} eV and 6×10^{19} eV, the integrated flux for $p = 2$ and $\epsilon = 0.3$ remains about an order of magnitude below the observed flux above $10^{19.3}$ eV. However, the right panel of Fig. 1 shows that there are solutions within our parameter space that allow an injection flux up to 10 times larger than that observed at Earth, which could result in higher fluxes after propagation. In addition, although this study considers only a single source located at the distance of Centaurus A, the observed flux could originate from the combined contributions of multiple radio galaxies at different distances undergoing the same process.

On the other hand, the composition assumed in our model contains too little iron to explain the spectrum above 6×10^{19} eV, and the model also fails to reproduce the flux below 6×10^{18} eV, suggesting that an additional component may be required in this energy range. All of these scenarios and limitations will be discussed in more detail in a forthcoming paper (Müller et al., in prep).

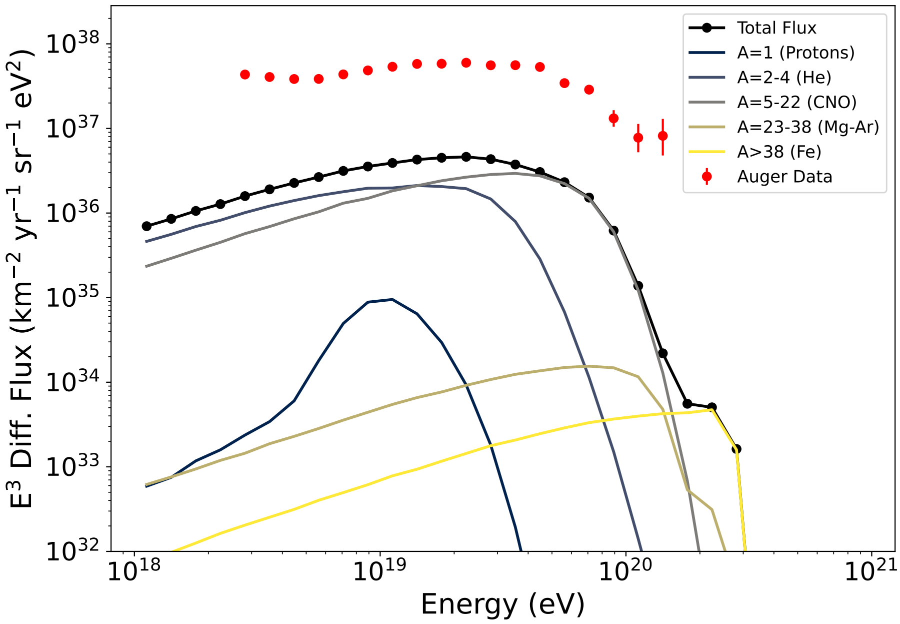

Figure 2: Energy spectrum observed at Earth after propagation from a distance of 3.8 Mpc, for initial particle distributions with spectral index $p = 2$ and composition fractions determined by our WR model.

4. Conclusions

Our results indicate that the interaction of WR stars with AGN jets can enhance the jet metallicity. Stellar winds from WR stars might inject significant amounts of carbon, nitrogen, oxygen, and heavier nuclei into the AGN jet via efficient mixing driven by fluid instabilities. The fraction of elements contributed by a single WR star enables UHECR flux calculations at the source that can be consistent with Pierre Auger Observatory measurements under certain assumptions. Specifically, we initially assumed that (i) all wind particles are loaded into the jet ($\dot{M}_{\rm mix} = \dot{M}_{\rm WR}$) and (ii) 30% of the jet luminosity is converted into UHECR luminosity. However, our analysis shows that only a portion of the wind material can be accelerated within this jet power fraction, so assumption (i) is not a strict requirement.

On the other hand, we find that the mass composition and injection assumptions produce an energy spectrum that is similar to observations in both shape and composition after propagation effects are included. When considering only Centaurus A with initial cosmic-ray particle distributions of spectral index $p = 2$, our model can account for up to $\sim 10\%$ of the observed UHECR flux above $10^{19.3}$ eV. Nonetheless, there exist parameter combinations that allow for larger fluxes at the source, potentially reconciling differences between observational data and the propagated fluxes predicted by our model. Furthermore, although this study considers only a single source at 3.8 Mpc, the total observed UHECR flux may result from the combined contributions of a population of radiogalaxies undergoing the same acceleration process.

While our model reproduces the observed UHECR spectrum between 6×10^{18} eV and 6×10^{19} eV reasonably well, it underpredicts the flux below 6×10^{18} eV, indicating that other types of sources may be required, and it also underpredicts the highest-energy events above 6×10^{19} eV, where a larger fraction of iron would be necessary. Despite these limitations, the model provides viable solutions consistent with the observed mass composition and a broad parameter space capable of producing fluxes compatible with observations. Future work will explore the wider range of parameters and relax some of the current assumptions to further refine the model.

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