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Active Galactic Nuclei Metallicity Enrichment and UHECR Composition

Ana Laura Müller[a,*] **and Anabella Araudo**[a]

[a] *FZU - Institute of Physics of the Czech Academy of Sciences,*
Na Slovance 1999/2, 182 00 Prague 8, Czechia

E-mail: `mulleral@fzu.cz`, `araudo@fzu.cz`

The origin of ultra-high-energy cosmic rays (UHECRs) remains a major open question in astrophysics. Observational data suggest that starburst galaxies and active galactic nuclei (AGN) are the most promising sources. However, accelerating particles to energies above 1 EeV in these environments is complex due to the demanding requirements on energy, density, and metallicity imposed by observations. In this work, we explore the theoretical challenge of explaining the presence of intermediate and heavy nuclei within the context of AGNs. The interaction of AGN jets with the winds of embedded stars leads to turbulent mixing and jet mass loading. The winds of Wolf-Rayet stars are rich in nuclei of Carbon-Nitrogen-Oxygen, and in this contribution we focus on the role of Wolf-Rayet stars in enhancing the metallicity of AGN jets. We estimate the flux of UHECRs from a Centaurus A-like radiogalaxy and find it to be comparable to the fluxes observed by the Pierre Auger Observatory under certain assumptions. We conclude that the proposed scenario is potentially one that could shed light on the sources of UHECRs.

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1. Introduction

Starburst galaxies and active galactic nuclei (AGN) have long been candidates for accelerating ultra-high-energy cosmic rays (UHECRs). Over the past decade, this hypothesis has received experimental support from the Pierre Auger Collaboration analyses on the correlation of arrival directions of UHECRs. Although these studies do not reach a level of statistical significance, they suggest some correlation with both types of sources [1]. However, the mass composition inferred from UHECR events above $10^{19.3}$ eV suggests that they are likely to originate in environments rich in intermediate-mass nuclei, such as Carbon-Nitrogen-Oxygen (CNO) [2]. In starburst galaxies, the presence of CNO is expected due to their large star formation rates. However, these galaxies do not seem to have enough energy budget to accelerate UHECRs. According to the "Hillas-Lovelace" limit, accelerating a particle with atomic number $Z_{\rm A}$ up to 10^{19} eV requires the source to have a kinetic power of at least $\sim 10^{44}\, Z_{\rm A}^{-2}$ erg s^{-1}, which is well above the kinetic power of starburst galaxies (e.g. [3]).

Radiogalaxies are the subclass of AGN where jets are clearly detected at radio frequencies. Their jet kinetic power is 10^{42} erg s$^{-1} \leq L_{\rm jet} \leq 10^{48}$ erg s^{-1}, satisfying the energetic requirement to accelerate UHECRs. Jets from radiogalaxies are expected to be mainly composed of leptons, but the deceleration observed in many AGN jets suggests that they should be mass-loaded with baryons (e.g., [4]). One of the proposed mechanisms to explain the entrainment of protons and nuclei in these jets is through the interaction with embedded stars. Previous studies focused on jet-mass loading from red giant stars. These stars are expected to be abundant around jets but not particularly rich in CNO elements [5].

In this work, we address the theoretical challenge of explaining the presence of intermediate and heavy nuclei in jets from radiogalaxies. We explore whether the interaction between an AGN jet and a single Wolf-Rayet (WR) star can significantly enhance the metallicity of the jet. WR stars are particularly interesting in this context, as they have large mass-loss rates and their winds are rich in CNO elements, with a composition that aligns with the abundances detected in cosmic rays [6]. We investigate whether, in this scenario, a source such as Centaurus A could account for the UHECR fluxes observed by the Pierre Auger Observatory.

2. Model

We consider a Centaurus A-like radiogalaxy as a case study, see Table 1 [7]. Centaurus A is the nearest radiogalaxy and it is located inside the hotspot reported by the Pierre Auger Collaboration [1]. We model the jet as conical with half-opening angle θ. The jet radius and density at a given distance z from the base are [8]

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

respectively, where $L_{\rm jet}$ is the jet power and Γ the jet bulk Lorentz factor. To evaluate the probability of having at least one WR star inside the jet, we use the WR density from [9]

$$\frac{n_{\rm WR}(z)}{\rm pc^{-3}} \sim 3\times10^{-5}\,(497)^{y}\left(\frac{\eta_{\rm accr}}{0.1}\right)^{0.89}\left(\frac{M_{\rm BH}}{6\times10^{7}\,{\rm M_\odot}}\right)^{0.89}\left(\frac{z}{\rm pc}\right)^{-y}, \tag{2}$$

with $y = 1$ or $y = 2$. The total number of stars inside the jet up to a distance z is

$$N_{\rm WR}(z) = \int_{1\,\rm pc}^{z} n_{\rm WR}(z')\, \pi\, R_{\rm jet}^2(z')\, dz', \tag{3}$$

where the minimum z distance is assumed to be 1 pc [10]. Figure 2 shows that at least one WR star is expected within the first 80 pc of the jet for $y = 1$, and in the first 7 pc for $y = 2$. This suggests that, although WR stars are relatively rare, the presence of at least one WR star inside the jet remains likely.

For the WR star, we consider the characteristic values listed in Table 1 [10]. The stellar wind density at a distance r from the star position is given by [9]

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

where $\dot{M}_{\rm WR}$ is the mass loss rate and $v_{\rm wind}$ is the terminal wind velocity. The encounter of the jet with the WR star leads to the formation of a double-bow shock structure with an stagnation point located at

$$\frac{R_{\rm sp}(z)}{R_{\rm jet}(z)} = \sqrt{\frac{\dot{M}_{\rm WR}\, v_{\rm wind}\, c}{4\, L_{\rm jet}}} \sim 3.8\times 10^{-2} \left(\frac{\dot{M}_{\rm WR}}{10^{-4} M_\odot {\rm yr}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm wind}}{3000\,{\rm km\,s^{-1}}}\right)^{\frac{1}{2}} \left(\frac{L_{\rm jet}}{10^{43}{\rm erg\,s^{-1}}}\right)^{-\frac{1}{2}} \tag{5}$$

from the center of the star. In Figure 1 we sketch this scenario.

Parameter	**Value**
AGN	
Jet power $L_{\rm jet}$	10^{43} erg s^{-1}
Black hole mass $M_{\rm BH}$	6×10^7 M$_\odot$
Accretion rate $\eta_{\rm accr}$	0.1
Half-opening angle θ	5°
Lorentz factor Γ	2
WR	
Mass-loss rate $\dot{M}_{\rm WR}$	10^{-4} M$_\odot$ yr^{-1}
Star lifetime τ	~ 5 Myr
Wind composition [^{12}C/^{4}He]	0.4 [1]
Wind terminal velocity $v_{\rm wind}$	3000 km s^{-1}

Table 1: Jet and star parameters.

The interface between the shocked stellar wind and the shocked jet material is expected to be turbulent due to velocity differences between the fluids. Instabilities, such as Kelvin-Helmholtz instabilities, develop and drive this turbulence, producing the mixing of wind material into the jet (see e.g., [11]). Assuming the characteristic length of the instability to be of the order of $R_{\rm sp}(z)$, the Kelvin-Helmholtz timescale reads [8]

$$t_{\rm KH}(z) = \frac{2\, R_{\rm sp}(z)}{c} \sqrt{\frac{\rho_{\rm wind}(z)}{\rho_{\rm jet}(z)(\Gamma - 1)}} \propto z. \tag{6}$$

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[1] Source for wind composition: [6].

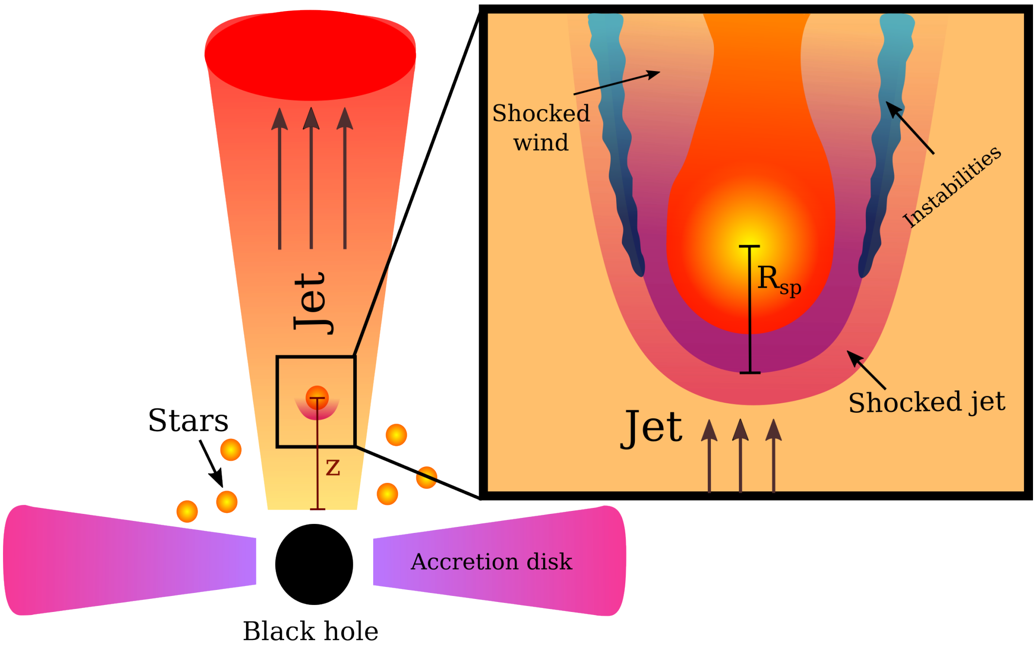

Figure 1: Sketch of the physical situation (not to scale).

On the other hand, the time needed by the star to cross the jet can be calculated as

$$t_{\rm cross}(z) = \frac{2\,R_{\rm jet}(z)}{v_{\rm K}(z)} \propto z^{3/2} \tag{7}$$

with $v_{\rm K}(z)$ the Keplerian velocity of the star. For our parameters, $t_{\rm KH}(z)/t_{\rm cross}(z) = 7{\times}10^{-3}(z/{\rm pc})^{-1/2}$, indicating that the instabilities develop long before the star exits the jet and the matter had enough time to mix efficiently when $z < 5 \times 10^{-5}$ pc. We assume the mixing rate to be $\dot{M}_{\rm mix} = \alpha\,\dot{M}_{\rm WR}$ with $\alpha \leq 1$. In this work we consider the limit case of $\alpha = 1$.

3. Results

Using $\dot{M}_{\rm mix} = \dot{M}_{\rm WR}$ and the composition fractions $\lambda_{\rm A}$ for protons (A=1), He (A=4), C (A=12), O (A=16), Ne (A=20), Mg (A=24), Si (A=28), and Fe (A=56), as given in [6] for the WR stellar wind model with ^{12}C/^{4}He = 0.4, we calculate the number of particles of each type entering the jet per unit time as

$$\Phi_{\rm A} = \lambda_{\rm A}\,\frac{\dot{M}_{\rm WR}}{m_{\rm A}} \tag{8}$$

where $m_{\rm A}$ is the mass of each element. We assume that all these particles $\Phi_{\rm A}$, with mass number A and atomic number $Z_{\rm A}$, are accelerated following a distribution function given by [12]

$$\frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E} = \kappa_{\rm A}\,E^{-p}\,e^{-E/E_{\rm A}^{\rm max}} \qquad \text{for } 10^{13}\ \text{eV} < \text{E} < \text{E}_{\rm A}^{\rm max} = 6 \times 10^{18}\,\text{Z}_{\rm A}\ \text{eV} \tag{9}$$

where the normalizations $\kappa_{\rm A}$ are calculated from

$$\Phi_{\rm A} = \int_{10^{13}\ {\rm eV}}^{E_{\rm A}^{\rm max}} \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\,{\rm d}E. \tag{10}$$

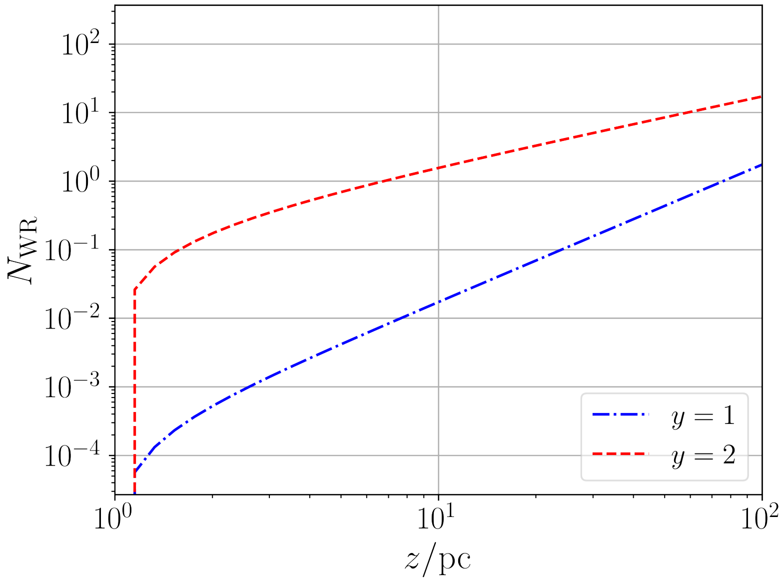

Figure 2: Cumulative number of WR stars inside the jet at a distance z.

In this work, we do not focus on any specific acceleration mechanism. We adopt p as a free parameter ranging from 1 to 2.7 to cover the parameter space of the known solutions for different acceleration mechanisms.

The total power that can be injected into particles of all types in the source is at most the jet luminosity $L_{\rm jet}$. Therefore, we compute a correction factor ξ to apply to all particle distributions, requesting

$$L_{\rm jet} = \xi \sum_{\rm A} \int_{10^{13}\ {\rm eV}}^{E_{\rm A}^{\rm max}} E\, \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\, {\rm d}E. \tag{11}$$

For the spectral indices $1 \leq p \leq 2.7$, ξ falls within the range $7 \times 10^{-9} \leq \xi \leq 3 \times 10^{-4}$. This indicates that the jet energy budget is sufficient to accelerate only a small fraction of the total particles entrained by wind mixing.

According to the results of the Pierre Auger Collaboration, the UHECR spectrum from $10^{19.3}$ eV to $10^{20.2}$ eV is dominated by CNO nuclei [2]. We calculate the integrated flux from a source located at distance D from Earth

$$J_{\rm UHECR}^{\rm source}(> 10^{19.3}\ {\rm eV}) = \frac{1}{4\,\pi\, D^2} \sum_{A>4} \int_{10^{19.3}\ {\rm eV}}^{10^{20.2}\ {\rm eV}} \xi\, E\, \frac{{\rm d}\dot{N}_{\rm A}}{{\rm d}E}\, {\rm d}E, \tag{12}$$

and compare it with the integrated flux measured by the Pierre Auger Observatory $J_{\rm Auger}(> 10^{19.3}\ {\rm eV}) = 8.4 \times 10^{37}$ erg Mpc^{-2} s^{-1} sr^{-1} [13]. In Fig. 3 we show $J_{\rm UHECR}^{\rm source}/J_{\rm Auger}(> 10^{19.3}\ {\rm eV})$ for $3.8 \leq D/{\rm Mpc} \leq 100$, where 3.8 Mpc is the distance to Centaurus A [7].

The flux predicted by our model matches the observations of the Pierre Auger Observatory for several combinations of spectral index and distance values. For a source at Centaurus A's distance (D = 3.8 Mpc), we obtain that $J_{\rm UHECR}(> 10^{19.3}\ {\rm eV}) \geq J_{\rm Auger}(> 10^{19.3}\ {\rm eV})$ when $p < 2.13$. This suggests that a single WR star can provide a sufficient number of nuclei to explain the integrated

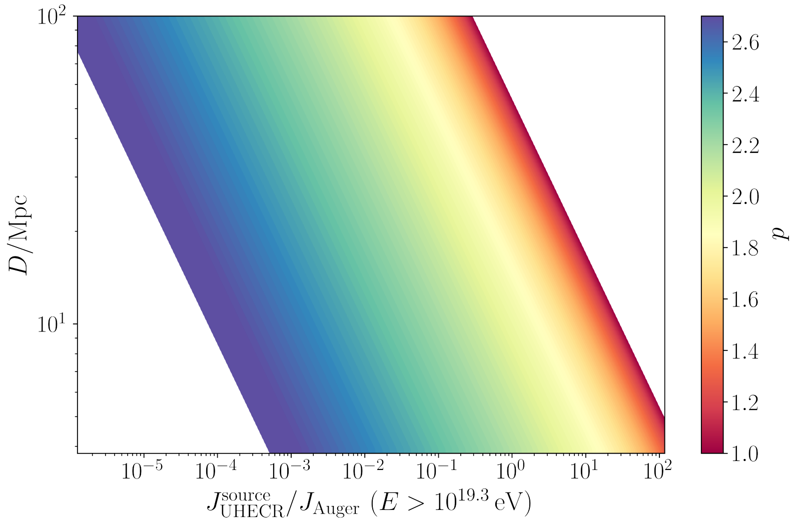

Figure 3: Fraction of the flux above $10^{19.3}$ eV produced by one WR star in a source injecting particles with different spectral indices p at different distances. Results shown in this plot correspond to $L_{\mathrm{jet}} = 10^{43}$ erg s^{-1}.

UHECR flux. Furthermore, multiple combinations of distance and spectral index result in an overprediction of the UHECR flux. This allows us to relax some assumptions, such as all particles being accelerated or the total jet power being fully converted into cosmic rays. On the other hand, considering a population of AGNs, rather than a single source as investigated in this work, could also make the model suppositions more flexible and compensate for the underpredictive models.

4. Conclusions

Our results show that the interaction of WR stars with AGN jets can significantly enhance the metallicity of the jets. The wind of WR stars can supply substantial amounts of carbon, nitrogen, oxygen, and heavier nuclei into the AGN jet through efficient mixing driven by fluid instabilities. The fraction of elements incorporated by a single WR star enables flux calculations that are consistent with the Pierre Auger Observatory data under certain conditions. We have assumed that i) all wind particles are loading the jet ($\dot{M}_{\mathrm{mix}} = \dot{M}_{\mathrm{WR}}$), and ii) all the jet luminosity goes to UHECRs (see Eq. 11). However, we have shown that only a fraction of the wind particles can be accelerated with the full power of the jet, meaning that assumption i) is not a strict condition. Furthermore, in the cases where the observed UHECR flux is overpredicted, assumption ii) can be relaxed so that only a fraction of the jet power (10^{43} erg s^{-1} in this work) is required to accelerate the particles, while still agreeing with the observational data. In conclusion, our model provides solutions consistent with the observed UHECR flux within the parameter space considered, even when the imposed conditions are modified. In a future work, we will explore a broader parameter space and relax the assumptions made in the present contribution.

Acknowledgments

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