Active Galactic Nuclei Metallicity Enrichment and UHECR Composition

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1. Introduction

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 (AGNs) 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 the observations. In this work, we explore the theoretical challenge of explaining the presence of intermediate and heavy nuclei within the context of AGNs. We will specifically focus on the contribution of a single Wolf-Rayet (WR) star in enhancing the metallicity of an AGN jet, particularly its role in increasing the presence of CNO elements. We discuss whether the enrichment due to the stellar wind interacting with the jet can account for the observed mass composition of UHECRs.

2. Model

AGN with Centaurus A parameters

- Jet power $L_{jet} = 10^{43}$ erg s^{-1}
- Black hole mass $M_{BH} = 6 \times 10^7\, M_\odot$
- Accretion rate $\eta_{accr}=0.1$
- Half-opening angle $\Theta=5°$
- Lorentz factor $\Gamma=2$
- Jet radius $R_{jet}(z) = z\tan(\Theta)$
- Jet density given by **[1]**

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

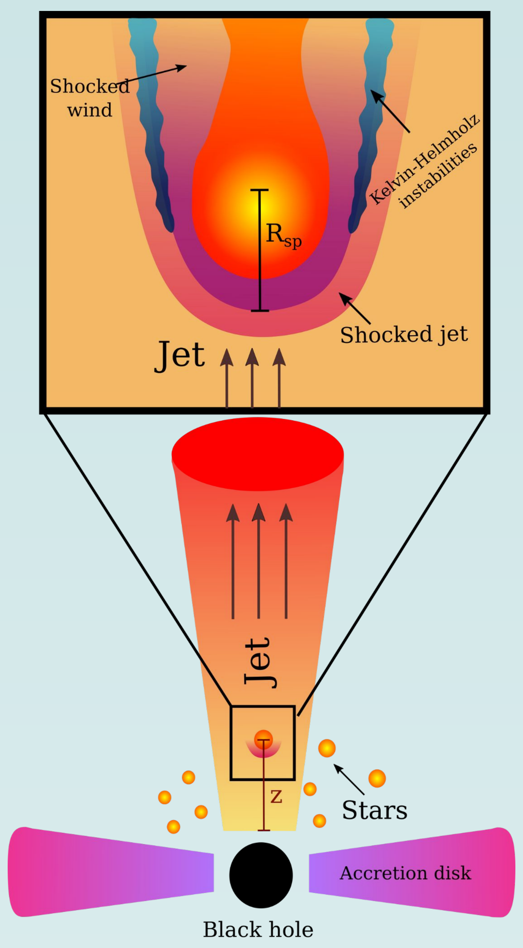

Figure 1: Sketch of the physical situation (not to scale).

WR star with typical parameters

- Mass-loss rate $\dot{M}_{WR} = 10^{-4}\, M_\odot$ yr^{-1}
- Lifetime $\tau \sim 5$ Myr
- Wind composition model [^{12}C/ ^{4}He] = 0.4 **[2]**
- Wind velocity v_{wind} = 2000 km s^{-1}
- Wind density **[3]**

$$\rho_{\rm wind}(z) = \frac{\dot{M}_{\rm WR}}{4\,\pi\, R_{\rm sp}^2(z)\, v_{\rm wind}} \propto z^{-2}$$

with

$$R_{\rm sp}(z) = \sqrt{\frac{\dot{M}_{\rm WR}\, v_{\rm wind}\, c\, R_{\rm jet}^2(z)}{4\, L_{\rm jet}}} \propto R_{\rm jet}(z) \propto z$$

the position of the stagnation point (see Fig. 1).

- Density of WR stars **[3]** with $y = 1$ or $y = 2$

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

Then, the total number of stars inside the jet up to a distance z is

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

Mixing due to **Kelvin-Helmholtz instabilities [1]**

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

Crossing time of the star through the jet

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

with $v_K(z)$ the Keplerian velocity of the star. For our parameters, $t_{KH}(z)/t_{cross}(z) = 7\times10^{-3}\,(z/{\rm pc})^{-1/2}$, indicating that the instabilities develop long before the star exits the jet.

Mixing rate $\dot{M}_{mix} = \alpha\, \dot{M}_{WR}$ with $\alpha \leq 1$. In this work, we consider the case $\alpha = 1$.

3. Results

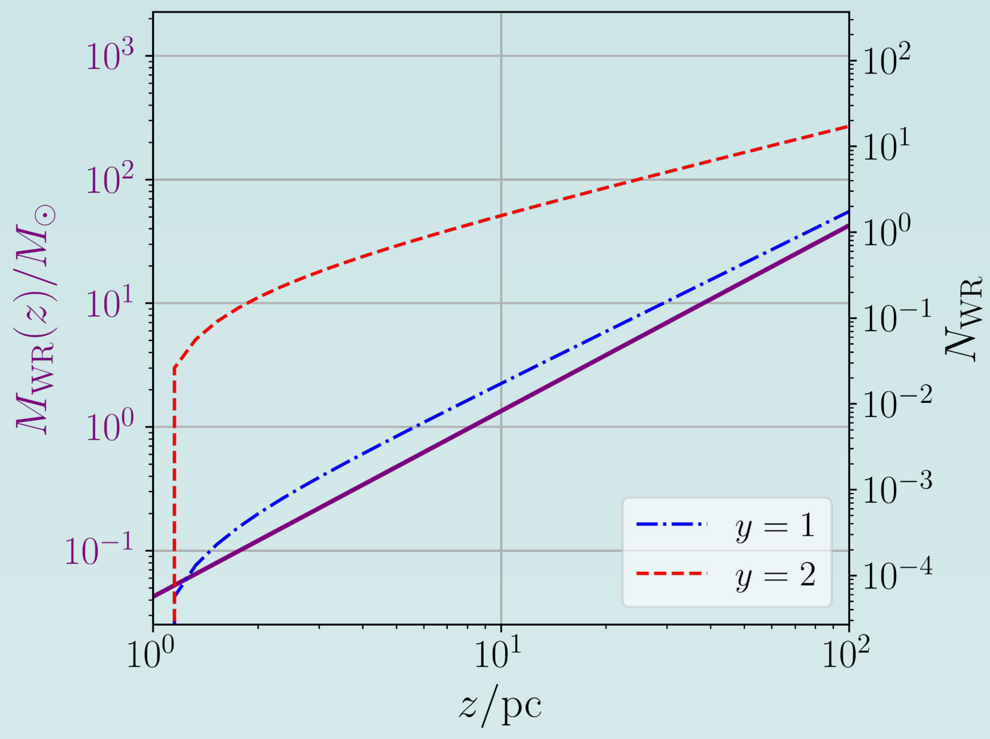

Figure 2: Total mass mixed during the cross of the star (left) and the cumulative number of WR stars inside the jet (right) at a distance *z*.

- In the first **100 pc of the jet, at least one WR star** is expected (see Fig. 2).
- From $\dot{M}_{mix} = \dot{M}_{WR}$ and the composition fractions λ_A for **proton** (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 **[2]** for the WR wind, the number of particles per unit of time of each type entering the jet can be calculated as

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

where m_A is the mass of each element.

- We assume all the particles Φ_A, with mass number A and atomic number Z_A, are accelerated following a distribution function given by **[4]**

$$\frac{d\dot{N}_{\rm A}}{dE} = \kappa_{\rm A}\, E^{-p}\, e^{-E/E_{\rm max}} \quad \text{for } 10^{13}\ {\rm eV} < E < E_{\rm max} = 6\times10^{18}\, Z_A\ {\rm eV}$$

where the normalizations κ_A are calculated from

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

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

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

- The UHECR spectrum is dominated by CNO nuclei above $\sim10^{19.3}$ eV **[5]**. Considering a distance *D* to the source, we calculate

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

and compare it with the flux measured by the Pierre Auger Observatory $J_{Auger}(>10^{19.3}\ {\rm eV}) = 8.4\times10^{37}$ erg Mpc^{-2} s^{-1} sr^{-1} **[6]** (see Fig. 3).

- We find that a single WR star provides sufficient nuclei to match the observed UHECR flux.
- Multiple combinations of distance and spectral index overpredict the observed UHECR flux. This allows us to relax some assumptions, such as all particles being accelerated or the total jet power fully converted into cosmic rays.
- A population of AGNs, instead of a single source, might compensate for the underpredictive models and further relax the assumptions.

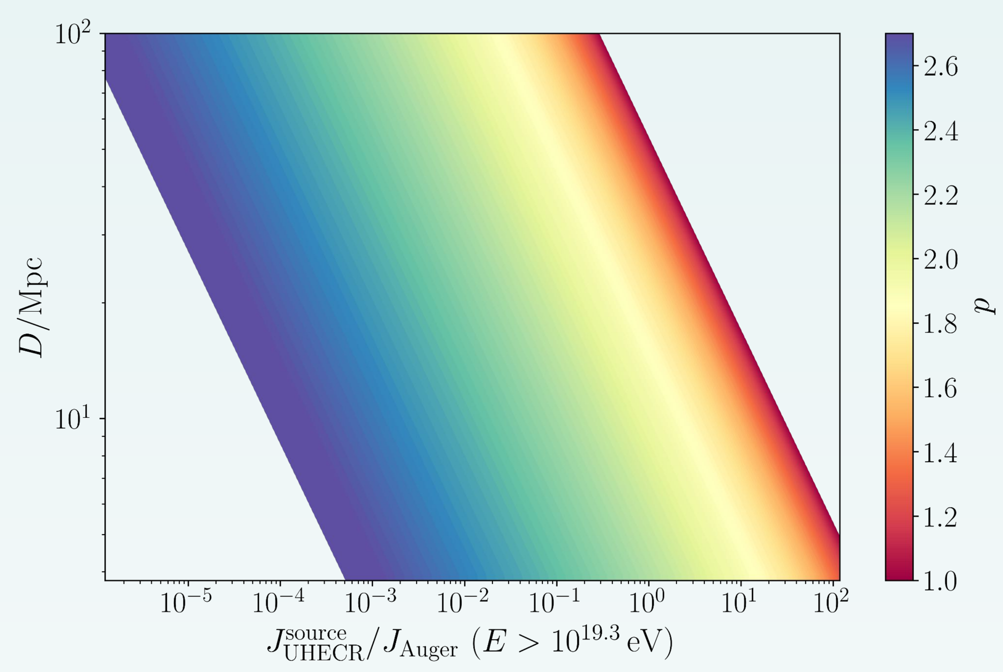

Figure 3: Fraction of the flux above $10^{19.3}$ eV produced by one star in a source injecting particles with different spectral indices *p* at different distances.

Acknowledgments

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4. Conclusions

Our results show that the interaction of WR stars with AGN jets can significantly enhance the metallicity of the jets. Through efficient mixing driven by fluid instabilities, the shocked wind of WR stars can supply substantial amounts of carbon, nitrogen, oxygen, and heavier nuclei into the AGN jet. The fraction of elements incorporated by a single WR star enables flux calculations that are consistent with the Pierre Auger Observatory data under certain assumptions. The robustness of this model is further supported by the possibility of relaxing some assumptions while still maintaining good agreement with the observed UHECR flux.