Cosmic-Ray Energy Dissipation Mechanisms in AGN Plasmas: Photopion, Collisional, and Synchrotron Losses

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Abstract

Cosmic rays are an important non-thermal component of active galactic nuclei (AGN) and may contribute significantly to the pressure balance and energy transport within galactic nuclei. The efficiency of cosmic-ray confinement and survival strongly depends on the surrounding plasma conditions, radiation fields, particle densities, and magnetic environments. In this study, we compare the dominant cosmic-ray energy loss mechanisms in quasars and Low-Ionization Nuclear Emission-line Regions (LINERs). We focus on photopion production, proton-proton collisions, magnetic diffusion, and synchrotron cooling processes. In quasar environments, intense radiation fields and strong magnetic activity enhance relativistic particle energy losses through photopion interactions and synchrotron emission. In contrast, the weaker radiation and magnetic environments of LINERs may allow cosmic rays to survive for longer timescales and contribute more effectively to sustained cosmic-ray pressure. Using characteristic physical parameters from both AGN classes, we discuss how environmental differences influence cosmic-ray evolution and pressure behavior. Our results suggest that quasars experience more efficient cosmic-ray energy dissipation, while LINERs provide comparatively stable conditions for cosmic-ray confinement.

1 Introduction

Cosmic rays play an important role in the energetic and dynamical evolution of active galactic nuclei (AGN). Their pressure contribution can influence plasma transport, magnetic turbulence, jet propagation, and the overall energy balance within galactic nuclei. The efficiency of cosmic-ray confinement and survival strongly depends on the surrounding radiation field, particle density, magnetic environment, and energy loss mechanisms operating inside the AGN [1, 9, 5].

Among AGN subclasses, quasars and Low-Ionization Nuclear Emission-line Regions (LINERs) exhibit significantly different physical environments [11, 3].

Quasars are characterized by intense radiation fields, high accretion rates, relativistic jets, and strong magnetic activity [11, 6]. In contrast, LINERs generally possess lower luminosities, weaker radiation fields, and lower plasma densities [4, 3]. These differences may substantially affect the evolution and pressure contribution of relativistic particles.

One of the most important energy loss mechanisms for relativistic protons is photopion production. This process becomes significant when the proton energy (E_p) and ambient photon energy (E_γ) satisfy the threshold condition

$$E_p E_\gamma \gtrsim 0.3 \text{ GeV}^2 \tag{1}$$

[10, 12]

In high-temperature environments such as quasars, the photon energy density is sufficiently large for this threshold to be exceeded frequently [12]. As a result, relativistic protons can interact with ambient photons and produce pions through processes such as

$$p + \gamma \to \Delta^+ \to p + \pi^0 \tag{2}$$

and

$$p + \gamma \to n + \pi^+. \tag{3}$$

These interactions redistribute particle momentum and transfer cosmic-ray energy into secondary particles and radiation, potentially reducing the effective cosmic-ray pressure.

In addition to photopion interactions, proton-proton collisions may also contribute to energy losses inside dense AGN environments. The collision rate depends on the ambient particle density and can be approximated as

$$t_{pp}^{-1} \sim n\sigma_{pp}c, \tag{4}$$

[7, 8]

where n is the particle density, σ_{pp} is the proton-proton interaction cross section, and c is the speed of light. High-density environments therefore enhance hadronic energy losses and shorten cosmic-ray survival times.

Magnetic fields also play a critical role in the transport and confinement of cosmic rays. The magnetic Reynolds number [9, 5],

$$R_m = \mu\sigma V L, \tag{5}$$

determines whether magnetic fields remain frozen into the plasma or diffuse through it. Variations in conductivity, turbulence, and collision frequency may either amplify magnetic fields through dynamo effects or weaken them through magnetic diffusion and reconnection processes. These effects directly influence synchrotron cooling and cosmic-ray propagation.

Relativistic electrons are particularly sensitive to synchrotron losses. The synchrotron power approximately scales as

$$P_{\text{sync}} \propto \frac{\gamma^2 B^2}{m^4}, \tag{6}$$

[8, 10]

where γ is the Lorentz factor, B is the magnetic field strength, and m is the particle mass. Due to their low mass, electrons lose energy much more rapidly than protons, especially in quasar environments where both magnetic field strength and Lorentz factors are large.

In this study, we compare the dominant cosmic-ray energy loss mechanisms in quasars and LINERs and investigate how these processes influence the resulting cosmic-ray pressure. By examining photopion production, particle collisions, magnetic diffusion, and synchrotron cooling together, we aim to explore how different AGN environments regulate the survival and dynamical importance of cosmic rays [11, 3].

2 Methodology

This study is based on a comparative theoretical analysis of cosmic-ray energy loss mechanisms in quasars and Low-Ionization Nuclear Emission-line Regions (LINERs). No direct observational measurements or new simulations are performed in this work. Instead, characteristic physical parameters reported in previous studies are used to investigate how different AGN environments influence cosmic-ray pressure and particle energy evolution.

Representative examples of quasars and LINERs will be selected from the literature, and their typical environmental properties such as magnetic field strength, photon energy density, plasma density, and characteristic particle energies will be compared [11, 3]. Average or commonly reported numerical values from published studies will be used throughout the analysis rather than source-specific observational measurements.

The study focuses on several major cosmic-ray energy loss mechanisms, including photopion production, proton-proton collisions, magnetic diffusion effects, and synchrotron cooling. The threshold condition for photopion production,

$$E_p E_\gamma \gtrsim 0.3\ \text{GeV}^2, \tag{7}$$

[10, 12] is used to evaluate the likelihood of hadronic interactions in different AGN environments. Since the ambient photon energy is related to temperature and radiation intensity, quasar environments are expected to exceed this threshold more frequently than LINERs.

Hadronic collision losses are examined using the approximate interaction timescale

$$t_{pp}^{-1} \sim n\sigma_{pp}c, \tag{8}$$

[7] where n represents the ambient particle density. Higher-density environments are expected to produce more frequent collisions and therefore stronger cosmic-ray energy dissipation.

Magnetic effects are discussed through the magnetic Reynolds number,

$$R_m = \mu \sigma V L, \tag{9}$$

which describes the balance between magnetic advection and diffusion processes in plasma environments. The possible influence of collision frequency and conductivity changes on magnetic field amplification or diffusion is considered qualitatively.

Electron synchrotron energy losses are evaluated using the proportional relation

$$P_{\text{sync}} \propto \frac{\gamma^2 B^2}{m^4}, \tag{10}$$

[8] where γ is the Lorentz factor and B is the magnetic field strength. This relation is used to compare the efficiency of synchrotron cooling in quasar and LINER environments.

The collected literature values and theoretical relations are then interpreted comparatively in order to discuss how environmental differences between quasars and LINERs affect cosmic-ray pressure evolution and particle survival times.

3 Results

In this section, characteristic parameter values from the literature are used to evaluate and compare cosmic-ray energy loss processes in quasar and LINER environments. No direct observations are performed; instead, representative average values are substituted into the theoretical framework described in the previous sections.

3.1 Adopted Typical Parameters

The following representative values are used:

Quasar:

- Magnetic field: $B \sim 0.1$ G
- Photon energy: $E_\gamma \sim 10$ eV
- Particle density: $n \sim 10^4$ cm^{-3}
- Electron Lorentz factor: $\gamma_e \sim 10^4$
- Proton Lorentz factor: $\gamma_p \sim 10^5$

LINER:

- Magnetic field: $B \sim 10^{-3}$ G
- Photon energy: $E_\gamma \sim 10^{-2}$ eV
- Particle density: $n \sim 10^2$ cm^{-3}
- Electron Lorentz factor: $\gamma_e \sim 10^3$
- Proton Lorentz factor: $\gamma_p \sim 10^3$

[3, 11, 6] —

3.2 Photopion Production Threshold

The interaction threshold is given by:

$$E_p E_\gamma \gtrsim 0.3 \text{ GeV}^2 \tag{11}$$

[12, 10] For quasars:

$$E_p \gtrsim \frac{0.3}{E_\gamma} \tag{12}$$
$$E_p \gtrsim \frac{0.3}{10 \text{ eV}} \tag{13}$$
$$E_p \gtrsim \frac{0.3}{10^{-8} \text{ GeV}} \tag{14}$$
$$E_p \gtrsim 3 \times 10^7 \text{ GeV} \tag{15}$$
$$E_p \gtrsim 3 \times 10^{16} \text{ eV} \tag{16}$$

For LINERs:

$$E_p \gtrsim \frac{0.3}{10^{-2} \text{ eV}} \tag{17}$$
$$E_p \gtrsim \frac{0.3}{10^{-11} \text{ GeV}} \tag{18}$$
$$E_p \gtrsim 3 \times 10^{10} \text{ GeV} \tag{19}$$
$$E_p \gtrsim 3 \times 10^{19} \text{ eV} \tag{20}$$

Result: Photopion interactions are $\sim 10^3$ times more easily triggered in quasars compared to LINERs.

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3.3 Proton-Proton Collision Timescale

$$t_{pp}^{-1} \sim n\sigma_{pp}c \tag{21}$$

[7] Using $\sigma_{pp} \sim 3 \times 10^{-26}$ cm^2 and $c = 3 \times 10^{10}$ cm/s:
Quasar:

$$t_{pp}^{-1} \sim (10^4)(3 \times 10^{-26})(3 \times 10^{10}) \tag{22}$$

$$t_{pp}^{-1} \sim 9 \times 10^{-12} \text{ s}^{-1} \tag{23}$$

$$t_{pp} \sim 1.1 \times 10^{11} \text{ s} \approx 3500 \text{ yr} \tag{24}$$

LINER:

$$t_{pp}^{-1} \sim (10^2)(3 \times 10^{-26})(3 \times 10^{10}) \tag{25}$$

$$t_{pp}^{-1} \sim 9 \times 10^{-14} \text{ s}^{-1} \tag{26}$$

$$t_{pp} \sim 1.1 \times 10^{13} \text{ s} \approx 350{,}000 \text{ yr} \tag{27}$$

Result: Hadronic cooling is $\sim$ 100 times faster in quasars.
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3.4 Thermal Pressure Comparison

$$P_{th} = nkT \tag{28}$$

[8] Assuming:
- Quasar: $T \sim 10^7$ K - LINER: $T \sim 10^6$ K - $k = 1.38 \times 10^{-16}$ erg/K
Quasar:

$$P_{th} = (10^4)(1.38 \times 10^{-16})(10^7) \tag{29}$$

$$P_{th} \sim 1.38 \times 10^{-5} \text{ erg/cm}^3 \tag{30}$$

LINER:

$$P_{th} = (10^2)(1.38 \times 10^{-16})(10^6) \tag{31}$$

$$P_{th} \sim 1.38 \times 10^{-8} \text{ erg/cm}^3 \tag{32}$$

Result: Thermal pressure in quasars is $\sim 10^3$ times larger.
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3.5 Synchrotron Cooling Scaling

$$P_{sync} \propto \gamma^2 B^2 \tag{33}$$

[8, 10] Relative comparison:

Quasar:

$$P_{sync,Q} \propto (10^4)^2(0.1)^2 = 10^8 \cdot 10^{-2} = 10^6$$

LINER:

$$P_{sync,L} \propto (10^3)^2(10^{-3})^2 = 10^6 \cdot 10^{-6} = 1$$

Result:

$$\frac{P_{sync,Q}}{P_{sync,L}} \sim 10^6$$

Synchrotron cooling is dramatically stronger in quasars.

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3.6 Overall Result

Combining all processes:

- Photopion production: ↑ quasar - Hadronic collisions: ↑ quasar - Synchrotron cooling: ↑↑ quasar - Particle survival time: ↑ LINER

Final conclusion:

Quasars exhibit significantly stronger cosmic-ray energy dissipation across all major channels, leading to reduced cosmic-ray confinement and pressure stability. In contrast, LINERs provide a lower-loss environment where cosmic rays can survive for longer timescales and contribute more effectively to sustained pressure support.

4 Discussion

The results indicate a strong environmental dependence of cosmic-ray energy loss mechanisms in active galactic nuclei. In quasar environments, the combination of high photon energy density, strong magnetic fields, and elevated particle densities leads to efficient energy dissipation of relativistic particles through photopion production, proton-proton collisions, and synchrotron radiation. These processes act collectively to reduce the lifetime and confinement efficiency of cosmic rays, thereby limiting their contribution to long-term pressure support within the nuclear region [6, 5].

In particular, the photopion threshold analysis demonstrates that quasar environments readily satisfy the condition $E_p E_\gamma \gtrsim 0.3\ \text{GeV}^2$, allowing frequent hadronic interactions. This leads to significant redistribution of proton energy into secondary particles and radiation channels. Similarly, the relatively short proton-proton interaction timescale in quasars further enhances hadronic cooling, reinforcing rapid energy dissipation [12].

The synchrotron scaling analysis shows an even stronger contrast between quasars and LINERs, with quasar synchrotron losses exceeding those of LINERs by several orders of magnitude. This implies that relativistic electrons in quasars lose energy efficiently before contributing significantly to large-scale cosmic-ray pressure. In contrast, LINER environments, characterized by weaker magnetic fields and lower Lorentz factors, allow electrons and protons to persist for longer timescales [8].

Magnetic field evolution also introduces competing effects. While high conductivity and turbulence in quasars can support dynamo amplification, increased collision rates and plasma instabilities may enhance magnetic diffusion and reconnection. The balance between these processes likely determines the effective magnetic structure and, consequently, the transport properties of cosmic rays.

Overall, the results suggest that quasars operate in a regime of strong energy dissipation and rapid particle cycling, while LINERs represent comparatively stable environments where cosmic rays can accumulate and contribute more steadily to pressure balance.

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5 Conclusion

This study provides a comparative theoretical analysis of cosmic-ray energy loss mechanisms in quasars and LINERs using representative literature-based parameter values. The analysis focused on photopion production, proton-proton collisions, magnetic field effects, and synchrotron cooling processes.

The results show that quasars exhibit significantly more efficient cosmic-ray energy loss due to higher photon energies, stronger magnetic fields, and denser plasma environments. These conditions lead to frequent hadronic interactions and strong radiative cooling, reducing the effective cosmic-ray confinement time and pressure contribution.

In contrast, LINER environments are characterized by lower radiation fields, weaker magnetic activity, and reduced particle densities. As a result, cosmic rays in LINERs experience fewer interactions and slower energy losses, allowing for longer survival times and more sustained pressure support.

The comparative framework developed in this work highlights the importance of environmental conditions in determining cosmic-ray dynamics in AGN. Future studies incorporating detailed numerical simulations and observational constraints could further refine these conclusions and quantify the relative contribution of cosmic rays to AGN feedback processes.

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