Constraining the Baryon Loading Factor of AGN Jets: Implication from the γ-Ray Emission of the Coma Cluster

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Abstract

High-energy cosmic rays (CRs) can be accelerated in the relativistic jets of active galactic nuclei (AGNs) powered by supermassive black holes. The baryon loading efficiency onto relativistic CR baryons from the accreting black holes is poorly constrained by observations so far. In this paper, we suggest that the γ-ray emission of galaxy clusters can be used to study the baryon loading factor of AGN jets, since CRs injected by AGN jets are completely confined in the galaxy clusters and sufficiently interact with the intracluster medium via a hadronic process, producing diffuse γ-rays. We study the propagation of CRs in the galaxy clusters and calculate the radial distribution of the γ-rays in the galaxy cluster with different injection rates from AGNs. By comparison with the γ-ray flux and upper limits of the Coma cluster measured by Fermi-LAT and VERITAS, we find the upper limit of the average baryon loading factor (defined as the efficiency with which the gravitational energy is converted into relativistic particles) to be ηp,gr < 0.1. The upper limit is much lower than that required to account for diffuse neutrino flux in the conventional blazar models.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Coma Cluster (270); Cosmic rays (329); γ-rays (637)

1. Introduction

Powerful relativistic jets generated by the accretions of the supermassive black holes (SMBHs), i.e., the active galactic nuclei (AGNs), are believed to be one of the promising acceleration sites of ultrahigh-energy cosmic rays (UHECRs; Biermann 1988; Takahara 1990; Rachen & Biermann 1993; Berezinsky et al. 2006; Dermer et al. 2009) and high-energy neutrinos (Mannheim et al. 1992; Atoyan & Dermer 2001; Murase et al. 2014). The baryon loading factor ηp,rad is usually defined as the ratio between total CR luminosity (Lp) and the bolometric radiation luminosity of the jet (Lγ), i.e., ηp,rad = Lp/Lγ. The baryon loading factor is very relevant to the UHECR and neutrino production processes. There have been some discussions regarding the baryon loading factor in AGN jets based on the lepto-hadronic model of blazars (e.g., Böttcher et al. 2013; Xue et al. 2019a), as well as the potential blazar neutrino events measured by IceCube (Eichmann et al. 2018; IceCube Collaboration et al. 2018a, 2018b; Taboada & Stein 2019; Gionmi et al. 2020; Paliya et al. 2020; Rodrigues et al. 2021). The accelerated protons or nuclei in blazar jets can interact with the radiation fields, which produces high-energy pions that eventually decay into photons and neutrinos. However, due to the constraints on the baryon loading factor in AGN jets based on the lepto-hadronic model of blazars (e.g., Böttcher et al. 2013; Xue et al. 2019a), as well as the potential blazar neutrino events measured by IceCube (Eichmann et al. 2018; IceCube Collaboration et al. 2018a, 2018b; Taboada & Stein 2019; Gionmi et al. 2020; Paliya et al. 2020; Rodrigues et al. 2021). The accelerated protons or nuclei in blazar jets can interact with the radiation fields, which produces high-energy pions that eventually decay into photons and neutrinos. However, due to the constraints on the baryon loading factor in AGN jets based on the lepto-hadronic model of blazars (e.g., Böttcher et al. 2013; Xue et al. 2019a), as well as the potential blazar neutrino events measured by IceCube (Eichmann et al. 2018; IceCube Collaboration et al. 2018a, 2018b; Taboada & Stein 2019; Gionmi et al. 2020; Paliya et al. 2020; Rodrigues et al. 2021). The accelerated protons or nuclei in blazar jets can interact with the radiation fields, which produces high-energy pions that eventually decay into photons and neutrinos. However, due to the constraints on the baryon loading factor in AGN jets based on the lepto-hadronic model of blazars (e.g., Böttcher et al. 2013; Xue et al. 2019a), as well as the potential blazar neutrino events measured by IceCube (Eichmann et al. 2018; IceCube Collaboration et al. 2018a, 2018b; Taboada & Stein 2019; Gionmi et al. 2020; Paliya et al. 2020; Rodrigues et al. 2021). The accelerated protons or nuclei in blazar jets can interact with the radiation fields, which produces high-energy pions that eventually decay into photons and neutrinos. However, due to the constraints on the baryon loading factor in AGN jets based on the lepto-hadronic model of blazars (e.g., Böttcher et al. 2013; Xue et al. 2019a), as well as the potential blazar neutrino events measured by IceCube (Eichmann et al. 2018; IceCube Collaboration et al. 2018a, 2018b; Taboada & Stein 2019; Gionmi et al. 2020; Paliya et al. 2020; Rodrigues et al. 2021).
The Coma cluster, located at a distance of \(\sim 100 \text{ Mpc} (z = 0.023)\), is one of the nearest and most massive galaxy clusters (Smith et al. 1998; Kubo et al. 2007). While the mass-to-energy conversion efficiency, denoted by \(\epsilon\), under the standard, radiatively efficient accretion disk model (Shakura & Sunyaev 1976) is \(\approx 0.1\), a higher efficiency, \(\epsilon \approx 0.3\), is also possible for thin-disk accretion onto a extreme Kerr black hole (Thorne 1974). Therefore, we adopt an intermediate value of \(W_0 \approx 0.2M_\text{BH, tot}c^2 \approx 2.1 \times 10^{53}\) erg to estimate the total gravitational energy extracted from black holes in the Coma cluster, where \(M_\text{BH} = 5.8 \times 10^{10} M_\odot\) is the total black hole mass (Ensslin et al. 1998). As jets are powered by accretions of SMBHs, the total energy of AGN jets should be less than or of the same order of magnitude as the releasing gravitational potential energy. Using the total amount of gravitational energy, we define a new baryon loading factor \((\eta_{\text{b, grav}})\) as the efficiency with which the gravitational energy is converted into relativistic particles in the present paper.

Multiwavelength observations and analysis ranging from low-frequency radio wavelengths to \(\gamma\)-rays centered in the direction of the Coma cluster have been reported (Kent & Gunn 1982; Ajello et al. 2009; Brunetti et al. 2012; Xi et al. 2018; Bonafede et al. 2021). The Coma cluster hosts a giant radio halo (Giovannini et al. 1993), and extended soft thermal X-ray emission is observed by the ROSAT all-sky survey (Briel et al. 1992). Using 9 yr of Fermi-LAT data, Xi et al. (2018) reported the discovery of \(\gamma\)-ray emission from the Coma cluster with an extended spatial structure. The integral energy flux of \(\gamma\)-ray emission in the energy range of 0.2–300 GeV is \(\sim 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\) with a relatively soft spectral index of \(\approx -2.7\) (Xi et al. 2018). The detection was later confirmed by the Fermi-LAT Collaboration (Abdollahi et al. 2020; Ballet et al. 2020), who found a source in the direction of the Coma cluster (named 4FGL J1256.9+2736 in the 4FGL-DR2 catalog), as well as by other groups (Adam et al. 2021; Baghmunday et al. 2021). Observations with the VERITAS \(\gamma\)-ray detector, High Energy Stereoscopic System telescopes, and other imaging atmospheric Cherenkov telescopes have also provided upper limits on the very high energy \(\gamma\)-ray flux of the Coma cluster (Perkins et al. 2006; Aharonian et al. 2009; Aleksić et al. 2012; Arlen et al. 2012). We will use these observations to constrain the baryon loading factor of AGN jets in the Coma cluster.

This paper is organized as follows. In Section 2, we study the propagation of CRs in the Coma cluster and calculate the radial distribution, taking into account the effects of two different injection histories. The observed \(\gamma\)-ray profile and the total flux of the Coma cluster are calculated in Section 3. The baryon loading factors are given in Section 4. We discuss the results and draw some conclusions in Section 5.

2. The Radial Density Profile of CRs in the Coma Cluster

Galaxy clusters are able to confine CRs for cosmological timescales (Völk et al. 1996; Berezhiani et al. 1997). The virial radius of the Coma cluster is \(r_{\text{vir}} \sim 3 \text{ Mpc}\) (Lokas & Mamon 2003; Kubo et al. 2007). As the typical scale of magnetic field fluctuations \(l_c\) is about 1%–10% of the virial radius (Brunetti & Jones 2015), we have \(l_c \sim 0.3 \text{ Mpc}\). The magnetic field strength of the Coma cluster can be derived from the Faraday rotation measures, \(B \sim 5 \mu \text{G}\) (Feretti et al. 1995; Bonafede et al. 2010). If the Larmor radius \(r_L\) of a proton or nucleus with change \(Z\) is smaller than the coherence length \(r_L < l_c\), which is satisfied with energy \(E_\gamma \lesssim 10^{21}Z(B/5 \mu \text{G}) (l_c/0.3 \text{ Mpc})\) eV, the propagation of CRs in the cluster turbulent magnetic field is in the diffusive regime (Kotera & Lemoine 2008).

In the diffusive regime, the diffusion coefficient is defined as

\[
D_\text{cl} = \left(\frac{B}{\delta B}\right)^2 cr_L^{-2}w_l^{-1} \approx 8.3 \times 10^{31} \left(\frac{l_c}{0.3 \text{ Mpc}}\right)^{2/3} \left(\frac{E_p}{1 \text{ PeV}}\right)^{1/3} \left(\frac{B/5 \mu \text{G}}{1 \text{ Mpc}}\right)^{-1/3} \text{ cm}^2\text{s}^{-1},
\]

where we have assumed \(B \sim \delta B\), and \(w = 5/3\) is the spectral index for Kolmogorov diffusion. The diffusion timescale of the CR in the Coma cluster is

\[
t_\text{diff} \approx \frac{1}{2D_\text{cl}} \approx 16.4 \left(\frac{r_{\text{vir}}}{3 \text{ Mpc}}\right)^2 \left(\frac{l_c}{0.3 \text{ Mpc}}\right)^{-2/3} \left(\frac{E_p}{1 \text{ PeV}}\right)^{-1/3} \left(\frac{B/5 \mu \text{G}}{1 \text{ Mpc}}\right)^{1/3} \text{ Gyr.}
\]

For CRs with \(E_p \lesssim 0.4 \text{ PeV}\), the diffusion timescale is longer than the Hubble time, \(t_H \sim 14 \text{ Gyr}\), so these CR protons are confined in the cluster by magnetic fields.

As CRs cannot escape the galaxy cluster, the radial distribution of accumulated CRs in the Coma cluster depends on the injection history of CRs, which determines the \(\gamma\)-ray production rate at present. We consider two reference cases of CR injection history as follows.

1. The overall AGN activity, which evolves over cosmic history, increases with redshift up to \(z \approx 2\) and then flattens (Hasinger et al. 2005; Ajello et al. 2012). As the CR injection is expected from the whole population of AGNs in the Coma cluster, the redshift evolution of AGN emissivities needs to be taken into consideration. We generally assume that the injection rate in the Coma cluster follows the AGN luminosity density injected into the universe as a function of redshift (or look-back time). The luminosity functions of both X-ray-selected (Hasinger et al. 2005) and Fermi-selected (Ajello et al. 2012) flat-spectrum radio quasars (FSRQ) samples have a similar profile, which peaks around redshift 1–2; the latter shows a steeper decline after the redshift peak. In this reference case, we use the luminosity density of the Fermi-selected sample to account for the injection rate, \(Q_\text{b}(t) \propto \overline{L}_{\text{inj}}\), where \(\overline{L}_{\text{inj}}\) is the look-back time.

2. Constant injection rate.

In this case, we consider a simple constant injection rate for a comparison, \(Q_\text{b}(t) = \text{const.}\). The injection time is assumed to last for \(\sim 10 \text{ Gyr}\).

The injected CRs at the sources are assumed to have a power-law spectrum, \(Q_\gamma(E_p, t) \propto E_p^{-\alpha}\). For the moment, we assume the spectrum following the one expected in the strong shocks, i.e., \(\alpha \approx 2\).

Neglecting the energy loss of particles and assuming that the particle injection occurs at \(r = 0\), the probability that the CR reaches a radius \(r\) after time \(t\) can be given by Aharonian...
In Figure 2, the contributions of different time intervals of the injection rate also in 10 TeV CRs is steeper than that of 1 PeV. The time evolution distribution of the CRs. As lower-energy CRs diffuse more quickly than higher-energy ones, the density distribution of 10 TeV CRs is steeper than that of 1 PeV. The time evolution of the injection rate also influences the density profile of the CRs. In Figure 2, the contributions of different time intervals are illustrated separately using different color scales.

As redshift evolution reaches a peak at the epoch z = 1–2 (Hasinger et al. 2005; Ajello et al. 2012), if the injection rate in the cluster follows the redshift evolution, the contributions of earlier injected CRs, which are currently diffused to a farther radius, are larger than those in the case of the constant injection rate. Therefore, for the case where the injection rate follows the redshift evolution case, the radial density distribution is flatter. Different redshift evolutions of luminosity density have a slight effect on the distribution compared to the constant case.

### 3. γ-Ray Production

The confined CRs interact with the ICM in the cluster via the pp interactions. The products of pp interaction are charged and neutral pions (π± and π0). Charged pions quickly decay into muons, then into electrons/positrons and neutrinos. Neutral pions decay into γ-ray photons, π0 → γ + γ. In this section, we focus on the production of γ-ray photons and calculate the radial profile of the γ-ray flux of the Coma cluster.

Following the calculation in Kelner et al. (2006), the γ-ray emissivity can be estimated as

$$J_\gamma(E_\gamma, r) = \frac{dN_\gamma}{dE_\gamma dV dt} = c \eta_{ICM}(r) \int_{E_p}^{\infty} \sigma_{pp}(E_p) \frac{dN_{pp}(E_p, r)}{dE_p dV} \times F_c \left( \frac{E_\gamma}{E_p} \right) \frac{dE_p}{E_p},$$

where $\sigma_{pp}(E_p)$ is the total inelastic cross section of the pp interactions, $F_c(E_\gamma/E_p, E_p)$ is the spectrum of the secondary γ-ray in a single collision, and $n_{ICM}(r)$ is the density profile of thermal gas in the ICM.

We use the classical “β model” of the density profile to describe the thermal gas in the ICM (Cavaliere & Fusco-Femiano 1976), which is

$$n_{ICM}(r) \approx n_{ICM}(0) \left[ 1 + (r/r_c)^2 \right]^{-3/2}.$$  (6)

The parameters of the ICM density profile can be measured from its bremsstrahlung emission in the X-ray wave band. For the Coma cluster, the parameters in Equation (6) are

$$n_{ICM}(0) = 3.42 \times 10^{-3} \text{ cm}^{-3},$$

$$r_c = 290 \text{ kpc} \sim 0.1r_{vir}, \beta = 0.75,$$

which are obtained from the X-ray all-sky survey of the ROSAT position-sensitive proportional counter (Briel et al. 1992).

Figure 3 shows the geometry between the Coma cluster and Earth with a spherical coordinate system, and the original point locates at the center of the Coma cluster. The luminosity distance of the Coma cluster is $R \approx 103$ Mpc, so the distance $D$ between the element volume $dV$ with coordinates $(r, \theta, \phi)$ and the Earth is $D = \sqrt{R^2 + r^2 - 2rr \sin \theta \cos \phi}$, and the viewing angle is $\psi \approx r \sin \theta \cos \phi / D$. Assuming spherical symmetry for the CR diffusion and ICM density profile, the γ-ray intensity profile average over the solid angle can be calculated as

$$\Phi(E_\gamma, \psi) = \frac{dN_\gamma}{dE_\gamma d\Omega dt} = \frac{1}{2\pi(1 - \cos \psi_{vir})} \int J_\gamma(E_\gamma, r) \frac{dV}{4\pi D^2} dV,$$  (8)

where $dV = r^2 \sin \theta dr d\theta d\phi$, $2\pi(1 - \cos \psi_{vir})$ is the solid angle of the γ-ray flux, and $\psi_{vir}$ is the angular distance of the virial radius.

We illustrate the γ-ray morphologies as a function of the viewing angle $\psi$ at different photon energies in Figure 4. As shown in Figure 4, the predicted γ-ray intensity profile follows the radial density distribution of both CRs and the gas. In both cases of injection history considered here, the γ-ray intensity profiles show flat cores and a steep decline at large radii.

### 4. Baryon Loading Factor in the Coma Cluster

#### 4.1. Time-averaged Baryon Loading Factor

In this section, using the total releasing gravitational potential energy $W_g$ as a denominator, we define the time-
the averaged baryon loading factor of the Coma cluster as

$$\eta_{b,\text{grav}} \approx \frac{W_{p,\text{tot}}}{W_g},$$  \hspace{1cm} (9)$$

where $W_{p,\text{tot}}$ is the total historical injected energy of the CRs, and $W_g$ is the total releasing gravitational potential energy from the central black hole, $W_g \approx 0.2M_{\text{BH}}c^2$.

The total mass of the central black hole of AGNs in the Coma cluster that is proportional to the total gravitational energy $W_g$ in Equation (9) can also linearly affect the results. Using the $M - \sigma$ relationship, the central black hole mass was suggested to be $\sim 10^{11}M_\odot$ (Kormendy & Ho 2013), given $\sigma \sim 1000$ km s$^{-1}$ in the Coma cluster. However, no such massive black hole has been found at the cluster center. The central black hole mass of one of the most massive supergiant elliptical galaxies, NGC 4889, is measured to be $M_{\text{BH}} = 2.1 \times 10^{10}M_\odot$ (McConnell et al. 2011). The ratio of the black hole mass to that of the spheroidal component of the stellar population of the host galaxy is estimated as $\eta_{bH} = 0.002-0.006$ (Kormendy & Richstone 1995; Wang & Biermann 1998). In this paper, we use a conservative value, $\eta_{bH} = 0.002$, corresponding to $M_{\text{BH}} \approx 5.8 \times 10^{10}M_\odot$ (Ensslin et al. 1998), to give the constraint.

The $\gamma$-ray photons produced via the $pp$ interaction will contribute to the total $\gamma$-ray flux from the cluster; we thus can use the observed $\gamma$-ray flux to restrict the total injection energy of protons. The absorption of $\gamma$-ray photons by extragalactic background light photons is not important for $\gamma$-rays below 10 TeV from a source at 100 Mpc. On the other hand, due to the streaming instability, CRs of energy less than tens of GeV may be dissipated by self-excited Alfvén waves (Kulsrud & Pearce 1969; Skilling 1971; see Appendix A for detailed calculations in the Coma cluster), so we use the highest energy bin of $\approx 55$ GeV in spectrum energy distributions of the extended emission component of the Coma cluster for the calculation.
single radio model from Xi et al. (2018) to restrict the total injection energy of CRs at a 95% confidence level.

Using this upper limit, we estimate the maximum allowed total injected energy of CR protons above 1 GeV and the corresponding baryon loading, \( \eta_{p,grav} \), for two different injection histories, as well as the power-law slope of the injection spectrum \( \alpha \). Since the expected pionic \( \gamma \)-ray flux at a certain energy depends on both of these parameters, the obtained constraints on the two parameters are coupled. The relationships between the \( \eta_{p,grav} \) and \( \alpha \) of the protons for two reference cases are shown separately in Figure 5. The best constraint is \( \eta_{p,grav} \leq 0.02 \) for the constant injection case and \( \leq 0.04 \) for the redshift evolution case when \( \alpha = 2.1 \). For softer spectral indices, the upper limit increases to \( \eta_{p,grav} \leq 0.1 \) for the redshift evolution case. In Figure 6, we compare the observed \( \gamma \)-ray flux with the theoretical prediction with the parameters \( \eta_{p,grav} \leq 0.04 \) (for the case of redshift evolution) and \( \alpha = 2.1 \). For the sake of illustration, the energy range below the highest energy bin of \( \approx 55 \text{ GeV} \) is shown by dotted lines and is not used for comparison, because the CR distribution at the lower energy range could be modified by the streaming instability.

Note that the streaming instability is less important at higher energy, where the particle number density is lower. A more conservative constraint can be obtained by using the 99% confidence level integral flux upper limit for \( E_{\gamma} > 220 \text{ GeV} \) in the Coma cluster core region (\( \psi = 0'74 \)) with the 18.6 hr VERITAS observation (Arlen et al. 2012).\(^3\) Arlen et al. (2012) provided three values of the upper limit under different assumptions of the \( \gamma \)-ray index, i.e., \(-2.1, -2.3, \) and \(-2.5 \). We here take the flux upper limit with \(-2.3 \) (which is \( \approx 4.7 \times 10^{-12} \text{ ph cm}^{-2} \text{s}^{-1} \)) for comparison with our theoretical prediction, noting that the difference from the given upper limits for \(-2.1 \) and \(-2.5 \) is only at a level of about 10%. The obtained constraints on \( \eta_{p,grav} \) with the VERITAS observation are shown in Figure 5. For softer spectral indices, the upper limit increases up to \( \eta_{p} \approx 1 \) in the redshift evolution case.

\(^3\) HESS also had a measurement on the Coma cluster, obtaining a higher flux upper limit (Aharonian et al. 2009), and hence is less constraining.
The Astrophysical Journal, 927:33 (9pp), 2022 March 1

Figure 7. Same as Figure 5, but only $\eta_{p,\text{rad}} = \eta_{p,\text{grav}}/\langle \eta_p \rangle$ for the redshift evolution case is shown. The dashed lines show results using the lower 95% confidence range of $\langle \eta_p \rangle$.

4.2. Radiation-related Baryon Loading Factor

The baryon loading factor defined in Murase et al. (2014) is $\eta_{p,\text{rad}} = L_p/L_{\gamma}$, where $L_p$ is the total CR luminosity, and $L_{\gamma}$ corresponds to the bolometric radiation luminosity of the jet. In this section, we use the total radiation energy $W_{\gamma}$ to obtain the baryon loading factor $\eta_{p,\text{rad}}$ for comparison.

Assuming that the total radiation energy is proportional to the black hole mass, we first use the total released gravitational energy to normalize the integral radiation energy, $\eta_{\gamma} = W_{\gamma}/W_{g}$.

Therefore, the baryon loading factor becomes $\eta_{p,\text{rad}} = W_{p,\text{tot}}/W_{\gamma} = \eta_{p,\text{grav}}/\langle \eta_p \rangle$, where $\langle \eta_p \rangle$ is the average fraction of integral radiation energy to the total released gravitational energy from observed blazars.

The sample is taken from Ghisellini et al. (2014) and composed of 191 FSRQs and 26 BL Lac objects. Because of the lack of measurements of the black hole mass for BL Lac objects, we only use the FSRQs from the sample to calculate $\eta_{\gamma}$ (see Appendix B for detailed calculations).

The baryon loading factors with different injection indexes are shown in Figure 7: $\eta_{p,\text{rad}} \lesssim 1$ (Fermi-LAT) and $\lesssim 10$ (VERITAS). Note that in the estimation of the modified baryon loading factor $\eta_{p,\text{rad}}$, the same normalization with the released gravitational energy of the black hole mass is used in $\eta_{p,\text{grav}}$ and $\eta_{\gamma}$. In the calculation of $\langle \eta_p \rangle$, the central black hole mass of each blazar in our sample is adopted. However, in the calculation of $\eta_{p,\text{grav}}$ in Section 4.1, as $W_{p,\text{tot}}$ accounts for the contributions of the total CR injection history in the Coma cluster, the released gravitational energy of the black hole mass is estimated by the total mass of the central black holes in the Coma cluster.

5. Discussions and Conclusions

Galaxy clusters can effectively confine the CRs in cosmological times, so CRs can sufficiently interact with the ICM to produce $\gamma$-ray and neutrino radiation. In this paper, taking into account the effects of the injection history of AGN jets, we have studied the propagation and distribution of CRs in the Coma cluster and obtained constraints on the average baryon loading factor using the $\gamma$-ray observations. The upper limits of the average baryon loading factor are $\eta_{p,\text{grav}} \sim 0.01$ and 0.1, respectively, from the Fermi-LAT and VERITAS observations for various CR power-law indexes. We also use the integral radiation energy to obtain the upper limits on the conventional baryon loading factor $\eta_{p,\text{rad}}$, which are $\eta_{p,\text{rad}} \sim 1$ (Fermi-LAT) and $\sim 10$ (VERITAS), respectively. If such a constraint can be generalized to all of the AGNs in the universe, one may conclude that blazars cannot be the major source of the diffuse neutrino background measured by IceCube, when comparing this upper limit to the theoretically required one (e.g., Murase et al. 2014; Palladino et al. 2019).

The $\gamma$-ray emission can also be produced by shocks associated with galaxy merger processes. The Coma cluster may be undergoing the merging process (Tribble 1993; Gurzadyan & Mazure 2001). Shocks associated with galaxy merger processes would also accelerate particles to relativistic energies and produce $\gamma$-ray emission (Colafrancesco & Blasi 1998; Ryu et al. 2003). In this scenario, the $\gamma$-ray profile is significantly different from the morphologies predicted by the central injection model in Figure 4 (Planck Collaboration et al. 2013; Ackermann et al. 2016). Hence, the $\gamma$-ray profile can be used to distinguish the two scenarios for the $\gamma$-ray emission. Note that, as our main purpose is to give the constraint on the upper limit of the baryonic loading efficiency, the $\gamma$-ray emission contributed by the galaxy merger does not affect our result and can only reduce the upper limits.

In this paper, we considered the total gravitational energy of the accretion matter as the upper limit of the energy budget for accelerated protons in AGN jets or outflows. We note that an analysis of the luminous blazar’s spectral energy distribution based on the conventional one-zone model shows that the jet/outflow’s power can be larger than the gravitational power of the accretion matter (Ghisellini et al. 2014). The general relativistic magnetohydrodynamic simulations of the radiative-inefficient accretion flow disks also show that the jet efficiency is allowed to be greater than unity for some parameters (McNamara et al. 2000). This may not be unreasonable; the accretion process can amplify the magnetic field, which means that the gravitational potential energy of the falling matter can be stored in the magnetic energy and released in a certain specific state. As a result, the instant jet/outflow power may exceed the accretion power. An observational constraint for the typical AGN phase lifetime is $\sim 10^5$ yr (Schawinski et al. 2015), and the typical timescale of the blazar flare duration is from days to months. Both timescales are much shorter compared to the total growth time $10^7$–$10^8$ yr of AGNs (Fabian & Iwasawa 1999; Yu & Tremaine 2002), or the Salpeter time. It implies that black holes grow via many such short bursts, so the time-averaged baryon loading factor $\eta_{p,\text{grav}}$ and $\eta_{p,\text{rad}}$ obtained in this paper might not apply to one short, specific status of AGNs, such as an intense flare.

Note that as the population of field galaxies is much larger than that inside clusters, the employed redshift evolution, which is obtained from the entire FSRQ population, may not be representative of AGNs in the clusters. Among many previous studies that are based on the Chandra X-ray survey and the Sloan Digital Sky Survey, some suggested significantly more suppression of the AGN fraction in clusters than in the field (Haggard et al. 2010; Haines et al. 2012; Hwang et al. 2012; Ehler et al. 2013, 2014), but some did not (Martini et al. 2013; Melnyk et al. 2013; Koulouridis et al. 2014). Such inconsistency among different studies is probably due to the observational bias (Xue 2017). If the AGN inside the cluster
has a stronger redshift evolution than that in the field, the constraint on the baryon loading factor will be relaxed, while if the AGN redshift evolution is weaker in the cluster than in the field, the constraint will be stricter.

As the acceleration timescale in AGN jets is much shorter than the cooling timescales in the energy range in our study, and CRs can escape faster than they efficiently interact in jets, we use a power-law spectrum to describe the CRs leaking into the cluster. However, if CRs are still confined in the AGN jets when the acceleration shuts off, they will lose energy via adiabatic cooling due to the expansion of the jet. This will reduce the energy of CRs leaking into the cluster and further increase the upper limit on the baryon loading factor.

The recent IceCube data show that the high-energy astrophysical muon–neutrino spectrum is consistent with a single power-law function (Abbasi et al. 2021). They also test the possible existence of an additional astrophysical component following a certain source class–specific flux prediction. These tests give independent constraints on the normalization of different theoretical models, which may be converted to constraints on the baryon loading factors. For example, the baryon loading factor $\eta_{\text{CR}} \text{rad}$ of AGN inner jets model from Murase et al. (2014) is $3 \sim 300$ and reduced to about half of the original value, $\sim 1-150$, based on IceCube’s constraint, which is generally in agreement with our result.

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Appendix A

CR Streaming in the Coma Cluster

The CR protons in clusters can stream along magnetic field lines down the CR gradient. As CRs stream in the plasma, a slight anisotropy in the CRs can generate unstable growth in the Alfvén waves, which is the so-called streaming instability (Kulsrud & Pearce 1969; Skilling 1971). The resulting wave growth rate can be written as (Kulsrud & Pearce 1969)

$$\Gamma_{\text{cr}} \sim \frac{\Omega_0 n_{\text{cr}} v_D}{n_i v_A},$$

(A1)

where $\Omega_0 = eB/(m_e c)$ is the cyclotron frequency, $n_{\text{cr}}$ is the number density of CR protons, and $n_i$ is the ion density in the plasma. The streaming speed $v_D$ can be written as $v_D = D(E_p) n_{\text{cr}} / n_{\text{cr}}$, and the Alfvén speed is $v_A = (eB)^{1/2}/(4\pi n_i m_p)^{1/2}$.

The wave would slow down CR diffusion and limit streaming speeds to the speed of the waves. However, there are a variety of damping mechanisms during the scattering, including nonlinear Landau damping in the collisionless limit and wave damping by background magnetohydrodynamic turbulence. The nonlinear Landau damping rate is (Kulsrud 2005)

$$\Gamma_{\text{NL}} \approx 0.3 \frac{\Omega_0}{\mu} \frac{v_i}{c} \left( \frac{\delta B}{B} \right)^2,$$

(A2)

where $\Omega_0 = \Omega / \gamma_p$, and $v_i$ is the velocity of thermal ions. The turbulence damping rate is (Farmer & Goldreich 2004)

$$\Gamma_{\text{turb}} \sim \frac{v_A}{\sqrt{r_B / \lambda}},$$

(A3)

where $r_B = \gamma_p m_e c/(eB)$, $l_A = L_{\text{MHD}}/M_A^3$, the injection scale in the ICM of the Coma cluster is $L_{\text{MHD}} = 300$ kpc, and the Alfvénic Mach number $M_A = 10$.

Figure A1 shows radius distributions of the growth and damping rates in the ICM of the Coma cluster for different proton energies. The loading factor $\eta_{\text{CR}} \text{rad}$ is 0.01 and $\alpha = 2$ for the constant injection case is adopted in the figure. When the energy of injected protons $E_p = 50$ GeV, the growth of the resonant wave exceeds the damping rate in the inner region of the cluster, which is also the main region of $\gamma$-ray production. When the energy of injected protons reaches 500 GeV (the corresponding energy of product $\gamma$-ray photons is $\sim$50 GeV), the streaming instability of CR transportation in the ICM is completely suppressed by damping mechanisms, so we can use the flux upper limit of the highest energy bin of the Fermi-LAT data to give the constraints.

Appendix B

Calculation of the Radiation Energy Fraction $\eta_{\gamma}$

In this appendix, we use a sample taken from Ghisellini et al. (2014) of 217 blazars (composed of 191 FSRQs and 26 BL Lac objects) that have been detected in the $\gamma$-ray band by Fermi-LAT and spectroscopically observed in the optical band. For blazars, using the one-zone leptonic model, the bolometric luminosity $L_{\text{bol}}$ can be established by multiwavelength data (Ghisellini & Tavecchio 2010; Ghisellini et al. 2014). The bulk Lorentz factor $\Gamma$ is determined by the viewing angle $\psi$, sin $\psi \sim 1/\Gamma$. Having the bolometric jet luminosity $L_{\text{bol}}$ and the bulk Lorentz factor $\Gamma$, the absolute radiative power $P_{\text{rad}}$ can be calculated as $P_{\text{rad}} = 2L_{\text{bol}}/\Gamma^2$, where the factor 2 accounts for two jets, and $f$ is the numerical factor for the external Compton process $(4/3)$ or the synchrotron and self-Compton emission $(16/5)$.
The distribution is fitted with a lognormal Gaussian distribution with an average value \( \langle \log_{10}(\eta) \rangle \approx -1.48 \) (\( \eta \approx 0.03 \)) and width \( \sigma \approx 0.67 \).

The Salpeter or e-folding time of an accreting black hole is estimated as \( t_{\text{Sal}} \approx 5 \times 10^7 \text{yr} \), which gives the characteristic timescale for the black hole mass to increase by one e-fold if the quasar's luminosity equals the Eddington limit (Salpeter 1964). If the characteristic growth time of black holes is comparable to the Salpeter time, and the growth of black hole mass occurs mainly during the AGN phases, the integral radiation energy can be estimated as \( W_\gamma = P_{\text{rad}}t_{\text{Sal}} \).

The fraction of integral radiation energy to the total released gravitational energy from black holes is defined as \( \eta_\gamma = W_\gamma / \epsilon_{\text{BH}} \cdot M_{\text{BH}} \), where \( M_{\text{BH}} \) is the central black hole mass. For FSRQs, the central black hole mass can be estimated through the virial H/3, Mg II, and C IV broad emission lines by reverberation mapping (Ghisellini et al. 2014). The histogram of \( \eta_\gamma \) from 191 FSRQs in the sample is shown in Figure B1. The distribution is fitted with a lognormal distribution. The average value \( \langle \eta_\gamma \rangle \approx 0.03 \), with a 95% confidence interval \( \eta_\gamma \in [0.007, 1.5] \). As the BL Lac objects have no central black hole mass estimation because of the lack of high signal-to-noise ratio broad-line measurements, we use the average black hole mass of the FSRQs to give a simple estimation of the 26 BL Lac objects in the sample, \( \log_{10}(M_{\text{BH}}/M_\odot) \approx 8.5 \), then \( \eta_{\text{BL}} \approx 0.03 \), which is in good agreement with that obtained with the FSRQs.

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The Astrophysical Journal, 927:33 (9pp), 2022 March 1 Shi et al.