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Relationship between Gamma-ray loudness and X-ray spectra of Radio Galaxies

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The *Fermi* satellite has detected ~60 radio galaxies (RGs). We investigate the difference in the properties of X-ray spectra between GeV-loud RGs and GeV-quiet RGs. Our sample comprises 68 objects: 36 GeV-loud RGs and 32 GeV-quiet RGs. For 68 RGs, we analyzed the X-ray spectra of the *XMM-Newton*, *Chandra*, *NuSTAR*, and *Swift*. Our results show that most GeV-loud RGs do not exhibit significant absorption, while ~50% of the GeV-quiet RGs exhibit significant absorption. This suggests that the jet of GeV-loud RGs is viewed from a small angle, and thus the radiation from the near to the SMBH is not easily blocked by the torus. Moreover, we reported that RGs with a heavy absorption is mostly in the X-ray luminosity range of $10^{43} - 10^{45}$erg s^{-1}; however, few RGs with lower and higher luminosity suffer from heavy absorption. This is the same trend as that of Seyfert galaxies.

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1. Introduction

Radio galaxies (RGs) are radio-loud Active galactic nuclei (AGN) with jets misaligned to the line of sight. RGs are classified in FR-I and FR-II based on their radio luminosity and morphology (Fanaroff & Riley [5]). Radio luminosity of FR-Is is less than 10^{26} W Hz^{-1} at 178 MHz, and radio flux is higher near the core and fades toward the outer region. Radio luminosity of FR-IIs is higher than 10^{26} W Hz^{-1} at 178 MHz, and radio flux is low close to the core and becomes bright toward the lobe edge region with bright hot spots. FR-I is considered to have a low mass accretion rate, while FR-II is considered to have a high mass accretion rate. Others that do not fall into this classification are Compact Steep Spectrum (CSS).

The jets of RGs are viewed at a larger angle from the line of sight. Therefore, the gamma-ray luminosity of RGs is lower than that of blazars by several orders of magnitude, and the number of detections in the GeV band is small. Therefore, it was difficult to statistically study the difference in properties between GeV-loud RGs and GeV-quiet RGs. However, with the 4th Fermi-LAT catalog (4FGL-DR2) [2], the number of RGs detected in the GeV gamma-ray band detections has increased and statistical analysis can be performed. Hereafter, we call *Fermi*-detected RGs as GeV-loud RGs and other RGs as GeV-quiet RGs. However, the number of RGs detected with *Fermi* is around 10% compared with those detected in the radio band, based on the comparison of logN-logS relation and flux ratio between radio and GeV gamma-ray bands [8]. Fukazawa et al. [7] systematically compiled the angle of the jets to be 10–30 degrees by the multi-wavelength Spectral Energy Distribution (SED) modeling with the Synchrotron Self-Compton (SSC) model for 10 RGs listed in the first Fermi-LAT catalog Abdo et al. [1]. However, their uncertainties are large. In addition, the SED of RGs consists of not only jet emission components but also other components from the host galaxy, disk/corona, and interstellar medium and thus SED modeling is often difficult.

In some cases, a viewing angle of jets was estimated from the radio flux ratio between two sides of the jet [6], but such cases of estimation are still limited. AGN emission from the central region close to the supermassive black hole (SMBH) can be observed as a power-law shape continuum emission in the X-ray band. AGN's central region is often surrounded by the torus. When the central region is viewed through this matter, X-ray continuum emission is observed as an absorbed power-law shape. About 80% of Seyfert galaxies with X-ray luminosity of $\sim 10^{43}$erg s^{-1} show a large absorption column density of $N_{\rm H} > 10^{22}$cm^{-2}; however, less than 50% of Seyfert galaxies with X-ray luminosity of $< 10^{42}$erg s^{-1} or $> 10^{44}$erg s^{-1} do [3, 4]. Since the jet direction is considered to be almost the same as the torus axis, we can know about the viewing angle of jets by using torus X-ray absorption. In previous reports (e.g. [9, 15]), the nature of the X-ray spectra of RGs have been statistically investigated, and a similar trend was found for RGs compared with radio-quiet AGNs. However, no comparison has been made between GeV-loud and GeV-quiet RGs, since the number of GeV-loud RGs has been limited. Therefore, a large number of RGs in the 4FGL-DR2 catalog for the first time enables us to compare the X-ray absorption between GeV-loud and GeV-quiet RGs. In this paper, we systematically analyzed available X-ray observational data of RGs and studied the dependence of X-ray absorption on gamma-ray detection. Cosmological parameters $(H_0, \Omega_m, \Omega_\Lambda)$ used in this study are $H_0 = 70\,{\rm km\,s^{-1}Mpc^{-1}}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

2. Sample and X-ray data

2.1 Sample Radio Galaxies

We use the 4FGL-DR2 catalog to select GeV-loud RGs, and radio flux-limited sample RG [12, 13] to select GeV-quiet RGs. The 4FGL-DR2 catalog was published [2] as the 4th Fermi/LAT Gamma-ray source catalog. The 4FGL-DR2 catalog contains 61 misaligned AGNs, of which 43 are classified as RG, 5 as CSS, and 11 as AGN[1]. Also, Mingo et al. [13] listed 45 RGs with fluxes of >2 Jy at 2.7 GHz. These are southern RGs and have a flat radio spectrum. Massaro et al. [12] compiled 93 RGs in the 3CR catalogue that have been observed in *Chandra*. We selected RGs for which X-ray data of the *XMM-Newton*, *Chandra*, *Swift*, or *NuSTAR* are available. If the X-ray emission can not be clearly seen at the RG position or most of the X-ray emission is extended, such RGs were excluded from our sample. We defined GeV-loud RGs in our sample as those listed in the 4FGL-DR2 catalog and selected 38 GeV-loud RGs. For GeV-quiet RGs, we first selected RGs from Mingo et al. [13], but their sample is poor in FR-Is while GeV-loud RGs are rich in FR-Is. Therefore, we selected FR-Is from Massaro et al. [12]. If RGs listed in Mingo et al. [13] or Massaro et al. [12] is also listed in 4FGL-DR2, we define them as GeV-loud RGs. Consequently, our sample contains 36 GeV-loud RGs (19 FR-I, 12 FR-II, and 5 CSS) and 32 GeV-quiet RGs (11 FR-I, 20 FR-II, and 1 CSS); a total of 68 RGs. For the detail of our sample, please check the Kayanoki & Fukazawa [10].

2.2 X-ray Data

X-ray data used in this study are obtained from the *XMM-Newton*, *Chandra*, *Swift*, and *NuSTAR*. The priority of the satellite data selection was *XMM-Newton*, *Chandra*, and *Swift* in that order. If the X-ray spectra suffer from significant absorption, the *NuSTAR* data were used. For multiple observations of the same object by the same satellite, the data with the highest photon count were used for *XMM-Newton*; moreover, the data with the longest observation time were used for the other three satellites. The *XMM-Newton* data were reprocessed and analyzed using Science Analysis System (SAS) version 19.0.0 and the latest calibration data CCF (Current Calibration Files) as of April 18, 2021. *Chandra* data were calibrated using version 4.12 of CIAO (Chandra Interactive Analysis of Observations) and version 4.9.3 of CALDB (calibration database), and spectra were created using `specextract`. *Swift* data were calibrated using `XRTPIPELINE` version 0.13.5 and CALDB version 20200724 of High Energy Astrophysics Science Archive Research Center (HEASARC). Spectral and ancillary response files were created using `xselect`. For *Nustar* data, data were calibrated using `NUPIPELINE` version 0.4.8 and version 20200912 of CALDB, and spectra were created using `nuproducts`.

3. Results

Table 2 of the Kayanoki & Fukazawa [10] summarizes the best-fit parameters obtained based on the spectral analysis. Error for each parameter is the 90% confidence interval. In addition, Table

[1]One of the object classes name in 4FGL-DR2. This class corresponds to non-blazar AGNs whose existing data do not allow an unambiguous determination of their AGN types.

3 of the Kayanoki & Fukazawa [10] shows the X-ray luminosity L_X and Eddington luminosity ratio for the power-law component. The luminosity of the power-law component is corrected for absorption. The 2-10 keV X-ray luminosity is in the range of 1.35×10^{40}–9.19×10^{45} erg s^{-1}. For the 64 objects whose BH mass was available, the estimated Eddington luminosity ratio for the X-ray power-law emission is mostly in the range of 6.54×10^{-7}–1.76. Also Table 4 of the Kayanoki & Fukazawa [10] shows a fraction of sources with absorption $N_{\rm H}$ greater than 10^{22}cm^{-2} for GeV-loud and GeV-quiet RGs. From this table, we can see that few GeV-loud RGs undergo absorption, while $\sim$ 50% of GeV-quiet RGs undergo absorption. Table 4 shows a fraction for each of the RG classifications. The fraction of sources with heavy absorption for FR-II RGs is as high as 40%, while that of others is $\leq$20%.

4. Discussion

4.1 Absorption $N_{\rm H}$ and Gamma-ray loudness

We reported that $\sim$ 50% of the GeV-quiet RGs have a large absorption column density $N_{\rm H}$, while few GeV-loud RGs have a large $N_{\rm H}$. The radiation from the center of AGNs is absorbed by the torus depending on the viewing angle. Therefore, the absorption is large when the torus is viewed from the side, while the absorption is small when it is viewed from a small inclination angle to the torus axis. Because the jet and torus axis are the same, we can assume that the viewing angle of the jet is smaller as the absorption becomes smaller. The jets of RGs could be brighter in gamma rays when the jet viewing angle is small and thus the beaming effect is large. This suggests that the GeV-loud RGs are observed from a relatively small viewing angle to the jet axis. When the jet is seen from a small angle, it is suggested that the X-ray radiation from the center of AGNs is not blocked by the torus and thus the absorption is small.

On the other hand, GeV-quiet RGs can be considered to have a weak jet beaming effect and thus gamma-ray radiation is faint, making them difficult to detect with Fermi. Therefore, we can assume that the GeV-quiet RGs are observed from a large viewing angle to the jet axis. In that case, we observe the center of AGNs through the torus. Therefore, it can be understood that the X-ray emission from the center of AGNs is easily blocked by the torus and most of the GeV-quiet RGs show absorbed spectra.

4.2 Absorption $N_{\rm H}$ and X-ray luminosity $L_{\rm x}$

From the fitting results, we created a scatter plot of the absorption column density $N_{\rm H}$ and X-ray luminosity (Figure 1). This figure shows that $\sim$ 50% of the medium-luminosity ($10^{43} - 10^{45}$ erg s^{-1} RGs show a large $N_{\rm H}$, while few of the low and high luminosity RGs show a large $N_{\rm H}$. The previous studies of the relationship between absorption and luminosity of RGs [11, 15] show the relation of mid- and high-luminosity RGs, and our results are consistent with these studies. Moreover, our result on low-luminosity RGs is novel.

In Seyfert galaxies, as shown by Beckmann et al. [3] and Burlon et al. [4], $\sim$ 50% of the medium-luminosity sources show a large $N_{\rm H}$, and few low and high luminosity sources show a large $N_{\rm H}$. This suggests that the absorption-luminosity relation for RGs, including low-luminosity RGs, follows the same trend as that for Seyfert galaxies. Because the fraction of AGNs with a

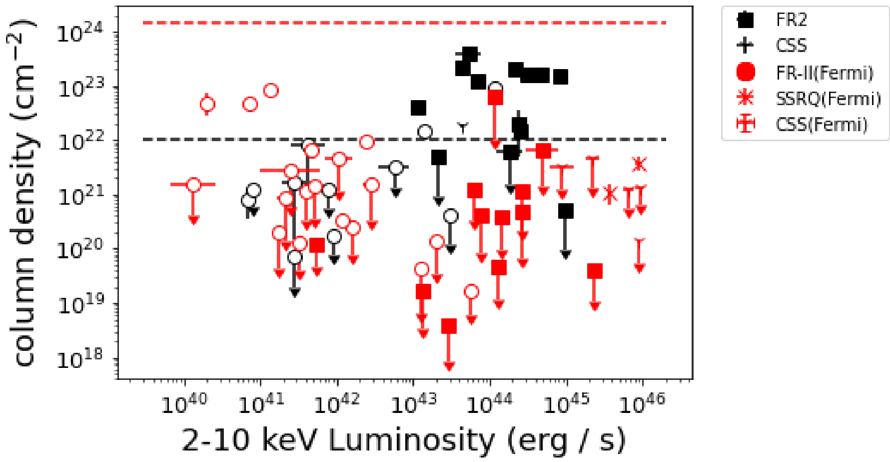

Figure 1: X-ray luminosity L_x vs Absorption column density N_H. The red color shows the GeV-loud RGs and the black color shows the GeV-quiet RGs.

large N_H at high luminosities is small, the dust torus is not formed with a large solid angle or a large thickness for brighter AGNs. This can be attributed to a physical process in which the high radiation flux from the center of AGNs affects the physical structure of the torus [**?**]. Similarly, the fraction of AGNs with a large N_H at low luminosities is small. It is suggested that the torus is not formed in low-luminosity ANGs (e.g., [4]). The same scenario can be applied to RGs, and thus they may not have a torus at low luminosities. Furthermore, as reported by Fukazawa et al. [7], the X-ray emission of low-luminosity RGs could be synchrotron radiation from the jet. In that case, the emission is not absorbed by the torus.

4.3 Photon index Γ_x and Eddington ratio $L_x/L_{\rm Edd}$

Figures 2 and 3 are a scatter plot of X-ray luminosity as well as the power-law index and that of the power-law index and absorption column density N_H. These figures demonstrated no dependence of photon index on N_H and X-ray luminosity. The average of photon index is 1.83 (0.46), 1.94 (0.42) and 1.70 (0.46) for all RGs, GeV-loud RGs, and GeV-quiet RGs, respectively, where values in the parentheses are standard deviation. It is 1.88 (0.47) and 1.70 (0.42) for RGs with NH$< 10^{22}$cm^{-2} and those with NH$> 10^{22}$cm^{-2}, respectively.

Sambruna et al. [16], reported weak evidence that Broad Line Radio Galaxies (BLRGs) have a flatter X-ray spectrum than that of the radio-quiet Seyfert 1 galaxies. Kang et al. [9] reported that the power-law photon index of RGs is flatter than that of radio-quiet AGNs. They analyzed the *NuSTAR* data of non-Compton-thick RGs and compared them with the results of [14] on radio-quiet AGNs. The average of photon index in Kang et al. [9] is 1.73 (0.15) and 1.90 (0.21) for RGs and radio-quiet AGNs, respectively.

Photon index 1.83 (0.46) for all RGs in our result is steeper than the photon index for RGs in Kang et al. [9]. Because the photon index of the GeV-loud RGs appears to be larger, we performed a KS test on the distribution of the photon index of GeV-loud RGs and that of GeV-quiet RGs and obtained a p-value of 0.3, indicating that the GeV-loud and GeV-quiet RGs have a significantly different photon index distribution. If the high-energy tail of synchrotron radiation from the jet is

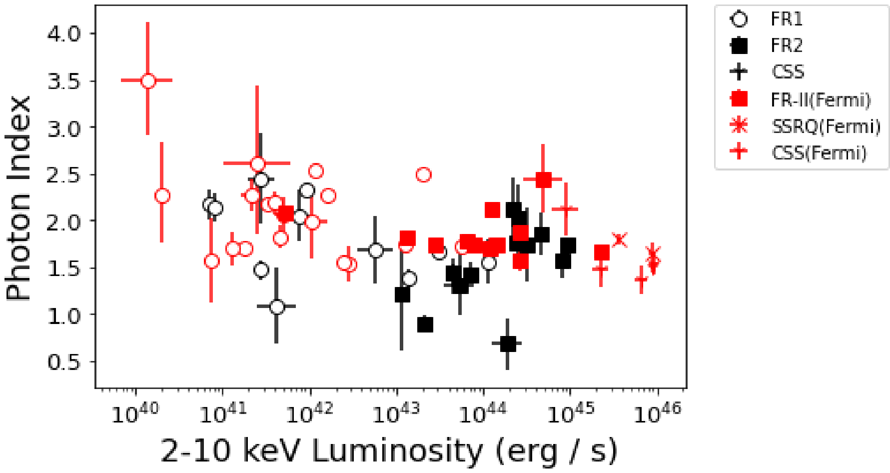

Figure 2: X-ray luminosity L_x vs photon index Γ_x. Markers are the same as figure 1

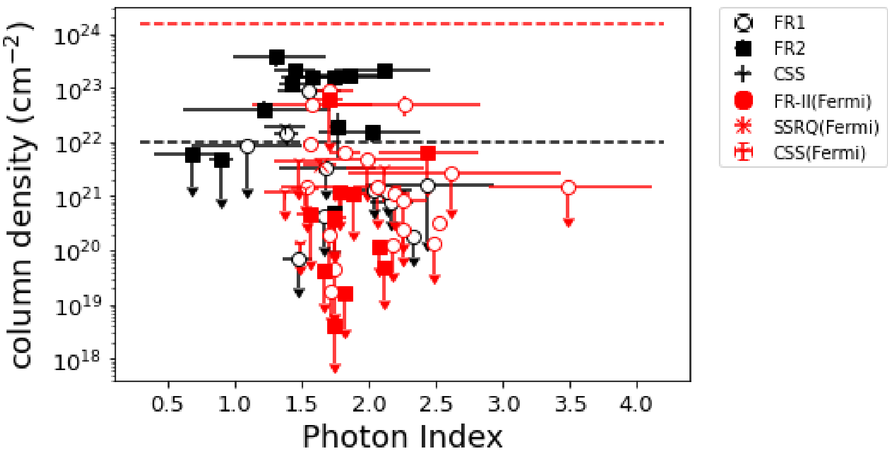

Figure 3: Photon index Γ_x vs Absorption column density N_H. Markers are the same as figure 1

observed in the X-ray band, the photon index is expected to be larger [7]; therefore, the photon index of GeV-loud RGs could be affected by the jet. The photon index of the GeV-quiet RGs may be flatter than that of the radio-quiet AGN [9]; however, because ~half of the GeV-quiet RGs suffer from the absorption, this flatness might be caused by the systematic effect from absorption. The Photon index could depend on the Eddington luminosity ratio. Therefore, we investigated the relation between the photon index and Eddington luminosity ratio; however, we do not identify any dependence within errors.

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