Radio Polarization of Blazars: Postprint

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Abstract

This study utilizes polarization data from 22 blazar sources in the UMRAO database to analyze and investigate the wavelength-dependent polarization of blazars in the radio band based on the theoretical model of Lazarian & Pogosyan, and to determine the causes of polarization variations with wavelength for different types of blazars. The results show good agreement with the theoretical model of Lazarian & Pogosyan. From this we draw the following conclusions: (1) In anomalous depolarization blazar sources, anomalous Faraday rotation plays a dominant role, while anomalous depolarization is relatively minor; (2) When thermal radiation mixes with synchrotron radiation, the degree of polarization in the high-frequency band is lower than that in the low-frequency band (anomalous depolarization); (3) When the wavelength of the observed band is shorter than the Wien wavelength corresponding to the thermal radiation from the accretion disk, the degree of polarization in the high-frequency band is greater than that in the low-frequency band (normal depolarization).

Full Text

Preamble

Polarization Study of Blazars in the Radio Band

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Abstract

In this paper, using polarization data for 22 blazar sources from the UMRAO database, we analyze the wavelength dependence of polarization in the radio band for blazars according to the theoretical model of Lazarian & Pogosyan, and derive the physical reasons for polarization variations with wavelength for different types of blazars. The results show good agreement with the theoretical model of Lazarian & Pogosyan. From this we draw the following conclusions: (1) In anomalous depolarization blazar sources, anomalous Faraday rotation plays a dominant role, while anomalous depolarization is relatively rare; (2) When thermal radiation and synchrotron radiation mix, the polarization degree in the high-frequency band is less than that in the low-frequency band (anomalous depolarization); (3) When the wavelength of the observed band is smaller than the Wien wavelength corresponding to the thermal radiation of the accretion disk, the polarization degree in the high-frequency band is greater than that in the low-frequency band (conventional depolarization).

Keywords: blazars; radio band; polarization; Faraday rotation; MHD

1. Introduction

As a subclass of active galactic nuclei (AGN), blazars are dominated by relativistic jets aligned with the observer' s line of sight [1]. These jets exhibit synchrotron radiation and strong linear polarization. The linear polarization degree can be calculated from the synchrotron radiation spectral index, while the magnetic field distribution can slightly alter polarization [2]. In this paper, we utilize observational results from the UMRAO database (https://dept.astro.lsa.umich.edu/datasets/umrao.php) to study the variation of blazar polarization degree with wavelength. The UMRAO database provides excellent data for investigating the polarization characteristics of blazars in the radio band.

Due to Faraday rotation, depolarization plays a role in the polarization degree of synchrotron radiation sources. The polarization can be expressed as $P \propto \lambda^{-2}$, where λ is the observed wavelength [3]. The Faraday rotation measure (RM) may be related to magnetic field topology [4][5], and a special magnetic field twisting effect exists [6][7]. Additionally, in recent studies, Marscher et al. proposed turbulent characteristics in Faraday RM, deriving a relationship where the RM structure function is related to the exponent of the turbulent energy cascade [8]. Some simulations also indicate that turbulence may be a cause of polarization variations in blazars [9]. In recent years, statistical correlation functions have been used to study three-dimensional anisotropic magnetohydrodynamics (MHD) to illustrate the effect of turbulence on wavelength-dependent polarization, showing that the MHD turbulence modeling results given by Lazarian & Pogosyan (2016) can be applied to analyze the radio band polarization in the UMRAO database.

This paper investigates depolarization characteristics in the radio band to reveal the physical reasons for wavelength-dependent polarization variations. We collected polarization data from UMRAO spanning September 2009 to May 2012, and performed power-law fitting of multi-band polarization degrees using

$P \propto \lambda^b$, where b is the fitting parameter. For blazars, we first verify the physical conditions of Faraday rotation given by Lazarian & Pogosyan (2016), and then provide the physical reasons for wavelength-dependent depolarization features.

2. Sample Selection and Fitting Results

It is generally believed that blazar polarization is produced by relativistic electron synchrotron radiation, which can be divided into single-electron and collective electron synchrotron radiation. Since blazar polarization is produced by a large number of electrons, we use collective electron synchrotron radiation to study blazar polarization and depolarization.

For collective electron synchrotron radiation, the spectral emissivity of electrons [10] is given by $j_\nu \propto \int N(\gamma) j_{\nu,\mathrm{single}}(\gamma) d\gamma$, where $N(\gamma)$ is the electron energy spectrum and $j_{\nu,\mathrm{single}}(\gamma)$ is the single relativistic electron synchrotron radiation spectrum. Typically, $\Omega \propto \sin\theta$. The electron energy spectrum follows a power-law distribution $N(\gamma) \propto \gamma^{-p}$, where γ is the electron Lorentz factor and p is the electron energy spectral index. The polarization degree produced by collective electron synchrotron radiation is then $P = \frac{p+1}{p+7/3}$, yielding polarization degrees between 60% and 82% for typical blazar spectral indices between 0 and 2. However, the actually measured polarization degree in the radio band is generally less than 10%, indicating that depolarization effects play a major role.

The above applies only to uniform radiation sources, whereas blazars are generally non-uniform emitters. Ballard et al. [11] proposed an expression to estimate the polarization of non-uniform sources: $P = \eta P_0$, where η represents the degree of magnetic field ordering, determined by the geometric properties of the magnetic field. This equation shows that the polarization degree is related to frequency (wavelength), and the polarization varies with wavelength, which is called WDP (wavelength dependence polarization).

There are multiple explanations for the cause of WDP. Magnetic field turbulence also has a certain influence on polarization (internal cause of depolarization). There are two primary reasons for WDP behavior: (1) the mixing of thermal radiation and synchrotron radiation produces WDP behavior; (2) WDP behavior inherently exists in synchrotron radiation [12].

Lazarian and Pogosyan [13] discussed the effects on polarization under Faraday rotation dominance and turbulence dominance, respectively. For wavelength-dependent polarization: (1) Under Faraday rotation dominance, the relationship is $P \propto \lambda^{-2}$; (2) Under turbulence dominance, the relationship is $P \propto \lambda^{-m}$, where m corresponds to the turbulent energy spectral index. The polarization variation with wavelength follows a power-law form. In reference [14], $P \propto \lambda^b$ was used to fit radio data from the UMRAO database to obtain b values for different sources. We continue to use this form for fitting, where b corresponds to the turbulent energy spectral index or the Faraday RM energy spectral index. If we assume $m = 2b$, the polarization variation with wavelength under turbulence dominance and Faraday rotation dominance produces consistent effects, so we take $m = 2b$ [13].

In selecting our sample, due to inconsistencies between different detectors, we only selected polarization data at 4.8 GHz, 8 GHz, and 14.5 GHz from the UMRAO database, and only for the period from September 2009 to May 2012. Among numerous AGN sources, we selected 22 blazar sources suitable for study. For these selected sources, the average observation period was 1 day, and no intense outbursts occurred between September 2009 and May 2012. Since the polarization data at the three bands were not quasi-simultaneous, and for convenience of study, we averaged their polarization values and errors separately to obtain three data points. For power-law fitting, three data points are sufficient to demonstrate the power-law behavior, making the fitting feasible. The UMRAO database data originate from observations by the NOEMA radio telescope, primarily intended for calibrating data obtained by other radio telescopes. The linear polarization in the database is partial linear polarization, and it only includes daily observations with polarization degree $P > 3\sigma_P$.

Figure 1 [Figure 1: see original paper] shows the power-law fitting for blazar sources with $b < 0$, where the horizontal axis is wavelength and the vertical axis is polarization degree. As shown in Figure 1, when b values are less than 0, the polarization degree decreases with wavelength, exhibiting anomalous depolarization. It is difficult to explain the physical mechanism producing $b < 0$ simply through MHD turbulence and Faraday rotation. The anomalous depolarization characteristic, where polarization increases with increasing wavelength, appears rarely in the optical band in reference [14], but occurs relatively frequently in our radio band, accounting for approximately 27% of blazar sources, nearly one-third. This phenomenon roughly implies that in about one-third of blazar jets, the polarization in the inner accretion disk is lower than that in the outer regions, equivalent to stronger magnetic fields in the periphery and weaker fields toward the interior, which is highly anomalous. This anomaly suggests that the magnetic fields in the accretion disk or jet of these one-third of blazars have likely become twisted. This twisting causes the magnetic fields in conventional synchrotron radiation and MHD models to be inconsistent with predictions in the data results. We believe this may be caused by turbulent magnetic reconnection, which leads to changes in magnetic field topology, converting magnetic energy into kinetic and thermal energy of the plasma and accelerating some charged particles within it. Part of the magnetic field in the accretion disk is dissipated, with the dissipated magnetic field converting into kinetic and thermal energy of the plasma and accelerating some particles, reducing the magnetic field inside the disk to below the strength of the peripheral magnetic field. Finally, thermal radiation mixes with synchrotron radiation, and anomalous Faraday rotation becomes dominant.

Figure 2 [Figure 2: see original paper] shows the power-law fitting for blazar sources with $b > 0$, where the horizontal axis is wavelength and the vertical axis is polarization degree. Figure 2 presents the case for $b > 0$, with 14 blazar sources. The polarization degree increases with wavelength, exhibiting conventional depolarization. This roughly indicates that in these blazar jets, the polarization in the inner accretion disk is higher than that in the outer regions, with weaker peripheral magnetic fields and stronger fields toward the interior, consistent with the magnetic field characteristics of synchrotron radiation. This situation accounts for approximately 70% of cases and represents the majority. When the observed band wavelength is smaller than the Wien wavelength corresponding to the thermal radiation of the accretion disk (the maximum wavelength of thermal radiation), the polarization degree in the high-frequency band is greater than that in the low-frequency band, consistent with predictions for the optical band in reference [17].

Figure 3 [Figure 3: see original paper] shows the distribution histogram of b values. It can be seen that the number of $b > 0$ cases is greater than $b < 0$ cases, indicating that conventional depolarization plays a dominant role in wavelength-dependent polarization variations. The b values are roughly distributed between 0 and 0.8, mainly concentrated between 0 and 0.4. Figure 4 shows the distribution of b values for each blazar source, clearly demonstrating that only 6 sources have $b < 0$, while the rest have $b > 0$.

Figure 5 [Figure 5: see original paper] shows the distribution of the turbulent index m when the regular magnetic field dominates. Each m value corresponds to the respective b value. We note that $m = 2/3$ corresponds to the three-dimensional anisotropic Kolmogorov spectrum.

Figure 6 [Figure 6: see original paper] shows the distribution of the turbulent index m when the turbulent magnetic field dominates. Each m value corresponds to the respective b value. We note that $m = 2/3$ corresponds to the three-dimensional anisotropic Kolmogorov spectrum.

The fitting results of the observed sample appear to be roughly consistent with both the regular magnetic field dominated (Faraday rotation dominated) case and the turbulent magnetic field dominated case. In Table 1 , we list the characteristics of polarization observations for each source, finding that the m_R values for OJ 287 and OR 103 are less than 0, which is inconsistent with the results in reference [14]. The possible cause could be insufficient data points or relatively large polarization variations within the data time period, leading to larger errors in the averaged data.

3. Discussion

In the fitting results, two sources (0420-014 and 0805-077) have $b \approx 0$ (polarization varies insignificantly with wavelength). Six sources exhibit $b < 0$ (anomalous depolarization), while fourteen sources show $b > 0$ (conventional depolarization). Blazar polarization mainly originates from synchrotron radiation, but the interstellar medium, accretion disk, broad-line region, etc., also affect polarization. In this paper, we only consider the effects of magnetic field turbulence and Faraday rotation, ignoring the above effects. Since we treat the electron energy spectrum as a simple power-law form, the intrinsic polarization degree is independent of wavelength and has no effect on the results.

We observe anomalous depolarization characteristics in the sample, where polarization increases with wavelength. Twisted magnetic fields can reduce anomalous Faraday rotation effects [15]. Therefore, both conventional depolarization ($b > 0$) and anomalous depolarization ($b < 0$) can occur. Recently, conventional depolarization characteristics have been discovered in some blazar jets [16]. In anomalous depolarization blazar sources, anomalous Faraday rotation plays a dominant role, while anomalous depolarization is relatively rare. The depolarization obtained in this sample demonstrates the polarization characteristics in jets: after mixing thermal radiation with synchrotron radiation, the polarization degree in the high-frequency band is less than that in the low-frequency band (anomalous depolarization); when the observed band is smaller than the Wien wavelength corresponding to the thermal radiation of the accretion disk (the maximum wavelength of thermal radiation), the polarization degree in the high-frequency band is greater than that in the low-frequency band [17] (conventional depolarization).

Lazarian & Pogosyan' s theoretical analysis shows that Faraday rotation fluctuations originate from anisotropic MHD turbulence. Our fitting statistical results in the blazar sample indicate that depolarization in the radio band roughly follows the Kolmogorov spectrum. Depolarization and related turbulent characteristics demonstrate the polarization diversity among different blazar sources.

For a given blazar, radio polarization at different wavelengths was not observed simultaneously or quasi-simultaneously in time, so the analysis and results in this paper, as well as their physical basis, may not be entirely appropriate. Additionally, as can be seen in this paper, for most blazars in the sample, the variation amplitude of polarization degree at different wavelengths is not large, with data from only three bands and a very narrow band range, which is not conducive to fitting and analysis.

The specific role and physical mechanism of magnetic field turbulence and magnetic field ordering mentioned in the article have important research value. We will further study these aspects in subsequent articles.

Note: Regarding the source types listed in Table 1, initially due to unfamiliarity with the SIMBAD database, we misclassified the sources, causing confusion and trouble for the reviewers. We sincerely apologize for this. In future studies, we will familiarize ourselves with database usage and will not make such errors again. We hereby express our deepest apologies.

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vised the paper according to the reviewers' suggestions. In future studies, we will extensively read literature to strengthen our knowledge.

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Note: Figure translations are in progress. See original paper for figures.