Polarization and Variations of BL Lacertae Objects

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Abstract

BL Lacertae objects are an extreme subclass of AGNs showing rapid and large-amplitude variability, high and variable polarization, and core-dominated radio emissions. If a strong beaming effect is the cause of the extreme observation properties, one would expect that these properties would be correlated with each other. Based on the relativistic beaming model, relationships between the polarization and the magnitude variation in brightness, as well as the core-dominance parameter are derived and used statistically to compare with the observational data of a BL Lacertae object sample. The statistical results are consistent with these correlations, which suggests that the polarization, the variation, and the core-dominance parameter are possible indications of the beaming effect.

Key words: BL Lacertae objects: general — galaxies: active — galaxies: jets — galaxies: nuclei — galaxies: photometry — polarization

1. Introduction

BL Lacertae objects are generally described as a subclass of active galactic nuclei (AGNs), showing rapid and large-amplitude variation, variable and high polarization, a core-dominated non-thermal continuum with some BL Lacertae objects showing superluminal motion and high-energy gamma-ray emissions (Angel, Stockman 1980; Antonucci, Ulvestad 1985; Fan et al. 1996; Cheng et al. 2000; Ghisellini et al. 1993; Hartman et al. 1999; Luna et al. 1993; Romero et al. 1995; Shakhovsky, Efimov 1999; Stickel et al. 1993; Takalo 1994; Wills et al. 1992; Xie et al. 1994). There are two subclasses of BL Lacertae objects, namely, the radio-selected BL Lacertae objects (RBLs) and the X-ray selected BL Lacertae objects (XBLs) from a survey or high-frequency peaked BL Lacertae objects (HBLs) and low-frequency peaked BL Lacertae objects (LBLs) from the spectral energy distribution (SED). RBLs correspond to LBLs, while XBLs generally correspond to HBLs.

The observational properties of RBLs are systematically different from those of XBLs. The latter have a flatter spectral energy distribution from the radio through X-ray regions, a higher starlight fraction, a higher observed peak of the emitted power from the radio through the X-ray spectral energy distribution and convex optical to X-ray continua. Furthermore, XBLs show lower polarization compared with RBLs, and they both occupy different regions in the effective spectral index plot (see Morris et al. 1990; Jannuzi et al. 1994; Giommi et al. 1995; Sambruna et al. 1996; Fan, Xie 1996; Fan et al. 1997).

Observations show that the polarization in Mkn 421 is correlated with the brightness of the source (Tosti et al. 1998); a similar phenomenon was also observed from 3C 345 (Smith 1996). Do the observations mean that there is a correlation between the polarization and the variation? In this paper, we discuss this correlation, and explain it in terms of a relativistic beaming effect. In section 2, a relation between the polarization and the variation is derived, and a comparison between the prediction and the observed data is presented. In section 3, we give some discussion and a conclusion.

2. Model

From the work of Padovani and Urry (1990) (see also Urry, Padovani 1995), the observed flux, \( S_{\text{obs}} \), of a relativistic jet is related to its intrinsic flux, \( S_{\text{i}} \), by \( S_{\text{obs}} = \delta S_{\text{i}} \), where \( \delta \), the Doppler factor of the jet, is defined by \( \delta = [\Gamma(1 - \beta \cos \theta)]^{-1} \), \( \beta \) is the velocity in units of the speed of the light, \( \Gamma = (1 - \beta^2)^{-1/2} \) is the Lorentz factor, and \( \theta \) is the viewing angle. The value of \( \delta \) depends on the shape of the emitted spectrum and the detailed physics of the jet (Lind, Blandford 1985), \( \beta = 3 + \alpha \) is for a moving sphere and \( \beta = 2 + \alpha \) is for the case of a continuous jet, where \( \alpha \) is the spectral index. However, because the emissions of an AGN can not be from the jet alone, it is natural for one to suppose that they are from two components, namely the beamed and the unbeamed ones. In this model, the observed total flux, \( S_{\text{obs}} \), is the sum of unbeamed, \( S_{\text{unb}} \), and beamed, \( S_{\text{i}} \), parts. Following the work of Urry and Shafer (1984; see also Urry, Padovani 1995), we assume that the intrinsic flux of the jet, \( S_{\text{i}} \), is some fixed fraction, \( f \), of the unbeamed flux, \( S_{\text{unb}} \), i.e., \( S_{\text{i}} = f S_{\text{unb}} \); we have \( S_{\text{obs}} = (1 + f \delta^2) S_{\text{unb}} \). For the case that \( f \) is not a constant, its effect on our results is discussed in section 3. Furthermore, the flux is not totally polarized in the jet, and it is not unreasonable to assume that the jet flux consists of two parts, namely, the polarized and unpolarized parts, with the two parts being proportional to each other, i.e., \( S_{\text{p}} = \eta S_{\text{unb}} \), \( S_{\text{up}} = S_{\text{unb}} \), where \( \eta \) is a coefficient which determines the polarization of the emission in the jet. The observed optical polarization can thus be expressed as

\[
p_{\text{obs}} = \frac{(1 + f) \delta^2}{1 + f \delta^2} p_{\text{in}} \quad (1)
\]
where the intrinsic polarization $P^{\text{in}}$, is defined by

$$P^{\text{in}} = \frac{f}{1 + f} \eta$$

(2)

and $\delta_0$ is the optical Doppler factor (Fan et al. 1997).

2.1. Correlation between the Polarization and the Variation

Using $S^{\text{ob}} = (1 + f \delta^2) S_{\text{unb}} = S_0 10^{-0.4 m^{\text{ob}}}$ and relation (1), we can obtain

$$\frac{10^{-0.4 m^{\text{ob}}}}{P_1^{\text{ob}}} = \frac{10^{-0.4 m^{\text{ob}}}}{P_2^{\text{ob}}} = k$$

(3)

from which follows

$$\frac{P_1^{\text{ob}}}{P_2^{\text{ob}}} = \frac{S^{\text{ob}}_1 - S_{\text{unb}}}{S^{\text{ob}}_2 - S_{\text{unb}}} = \frac{S^{\text{ob}}_1}{S^{\text{ob}}_2}$$

(4)

for the observations of any two epochs, where $P^{\text{ob}}$ and $m^{\text{ob}}$ are the observed polarization and magnitude, respectively, while $k$ is a constant of proportionality. Using $S^{\text{ob}} = \delta^{3+\alpha} S^{\min} + S_{\text{unb}}$, the ratio $\delta = (\delta_1/\delta_2)^{3+\alpha}$ can be expressed as

$$\eta = \frac{S^{\text{ob}}_1 - S_{\text{unb}}}{S^{\text{ob}}_2 - S_{\text{unb}}} = \frac{S^{\text{ob}}_1}{S^{\text{ob}}_2}$$

(5)

if $S^{\text{ob}}_1$ is greater than $S^{\text{ob}}_2$. In this sense, the ratio $\eta$ can be written in the form $\eta = (S^{\text{ob}}_1 / S^{\text{ob}}_2)^{\lambda}$, where the parameter $\lambda$ can be expected to be near unity, since $\delta^{3+\alpha} S^{\min}$ is usually much greater than $S_{\text{unb}}$. Thus, the ratio of polarizations

$$\frac{P_1^{\text{ob}}}{P_2^{\text{ob}}} = 10^{0.4(\lambda - 1) \Delta m}$$

(6)

where $\Delta m$ is the variation of magnitude, which follows

$$\log P_1 = 0.4(\lambda - 1) \Delta m + \log P_2$$

(7)

Relation (6) or (7), in principle, can be investigated based on the simultaneous observations of polarizations and magnitudes (or flux density). Unfortunately, for most objects, there are no simultaneous observations for polarization and magnitude. In this case, if we set $P_2$ to be the minimum polarization, $P_{\min}$, we obtain

$$\log P^{(\%)} = 0.4(\lambda - 1) \Delta m + \log P_{\min}$$

(8)

In order to avoid a possible observational bias (see section 3), we adopt the median polarization ($P_{\text{Med}}$) as $P$ and the largest amplitude variation ($\Delta m_{\text{Max}}$) as the variation $\Delta m$ in our discussion. The half value of the sum of the maximum and minimum polarization is taken as the median polarization ($P_{\text{Med}}$).

2.2. Results

From the available literature, we have compiled the corresponding maximum and the minimum optical polarizations to obtain the median polarizations, largest amplitude variation, and the core-dominance parameters for 35 BL Lacertae objects. They are listed in table 1, in which Column 1 gives the name, Columns 2 and 3 give the largest amplitude variation and the corresponding references; Columns 4 and 5 give the maximum and minimum optical polarization and the corresponding references; Columns 6 and 7 give the core-dominance parameter and the corresponding references. The core-dominance parameter, $R$, is defined as the ratio of the radio core flux density to the flux density in the extended lobes, and can be expressed as a function of the Doppler factor ($\delta$) and $f$, i.e., $R = f \delta^p$ (Ghisellini et al. 1993).

For PKS 1219+285 (ON 231), which has been observed for about 100 years, the early data observed by Wolf (1916) show that the object was as bright as 12 mag, which results in a largest amplitude variation of 5.4 mag. However, the 3 points discussed in the paper by Wolf (1916) are perhaps not certain, since they deviate from other observations by about 2.3 mag, if we do not take the 3 early points into account.

The largest variation is thus only 3.13 (Fan, Lin 2000a), which is adopted in the present work. For 1400+162, Jiang et al. (1999) obtained the VLBI total (165 mJy) and core (114 mJy) fluxes at 5 GHz, suggesting a core-dominance parameter of $R = (114/165 - 114) = 2.2$. The relevant points are shown in figure 1. When a least-squares regression fitting is performed to the median polarization and the largest amplitude variation for these 35 objects, the obtained result is

$$\log P^{(\%)} = (0.10 \pm 0.01) \Delta m + 0.72 \pm 0.04$$

(9)

with a correlation coefficient of $r = 0.641$ and a chance probability of $p = 6.32 \times 10^{-5}$. The best-fit result shown in figure 1 with a solid line implies that the parameters $\lambda = 1.25 \pm 0.12$ and $P_{\min} = 5.2\%$. In addition, the relation of $\eta$ gives $\log R_2 = 0.4\lambda \Delta m + \log R_1$, since $R = f \delta^{3+\alpha}$, which can be tested by observations if we let $R_2 = R_{\text{Max}}$, $R_1 = R_{\text{min}}$, and $\Delta m = \Delta m_{\text{Max}}$. Therefore, $\log R_{\text{Max}} = 0.4\lambda \Delta m_{\text{Max}} + c_1$; here $c_1$ is a constant associated with the minimum core-dominance, $R_{\text{min}}$. The fitting result, $\lambda = 1.25 \pm 0.12$, predicts that $\log R_{\text{Max}} = (0.50 \pm 0.05) \Delta m_{\text{Max}} + c_1$. When a linear regression was performed on the core-dominance parameter and the largest variation listed in table 1, a best-fit result, $\log R = (0.31 \pm 0.11) \Delta m + 0.39 \pm 0.40$, with a correlation coefficient $r = 0.45$ and a chance probability $p = 1\%$ was obtained. The best-fit result $0.31 \pm 0.11$ does not conflict with the predicted slope $0.50 \pm 0.05$.

3. Discussion and Conclusion

BL Lacertae objects are characterized by the observational properties mentioned in the introduction. The beaming model was adopted to explain both the particular observational properties and some observational differences between RBLs and XBLs (see Xie et al. 1991; Fan et al. 1993, 1997; Fan, Xie 1996; Georgopoulous, Marscher 1999), although the viewing angle alone can not explain all of the difference between the two subclass BL Lacertae objects (Sambruna et al. 1996). To discuss the intrinsic properties of BL Lacertae objects, one should know the boosting factor. Many authors have worked on this topic (Xie et al. 1991; Ghisellini et al. 1993; Lahteenmaki 1999; Fan et al. 1999). Recently, using the time variability, we determined the boosting factor and other physical parameters of Blazars (Cheng et al. 1999).

It is believed that the particularly observed properties of BL Lacertae objects are associated with the beaming effect; if so, there should be a correlation between those properties. In 1996, Smith reported that the polarization in 3C 345 is
and minimum polarization as the median polarization and used this value to investigate the correlation between the polarization and the variation for a sample of 35 BL Lacertae objects. Nevertheless, we have also used the observed maximum polarization to analyze equation (8); the correlation coefficient is 0.65. Although this chance probability is better than that of using the median polarization by a factor of 2, a possible observational bias may exist.

It is known that XBLs are not as strongly beamed, and that the observed data can be taken as the intrinsic data to some extent (Fan, Xie 1996). In this sense, the polarization of XBLs, which is ∼ 5% on average (see Jannuzi et al. 1994; Fan 1999), can be taken as the minimum polarization of BL Lacertae objects. The best-fit result for the polarization and the variation implies a minimum polarization of 5.2%, which is consistent with the observation result of XBLs (Jannuzi et al. 1994). Our results indicate that the polarization is correlated with the variation, which is also consistent with the observation results in both 3C 345 and Mkn 421.

The polarization is found to be associated with the core-dominance parameter (see Wills et al. 1992 and reference therein) with a high polarization corresponding to a large \( R \). From relation (3), one can obtain a relation between the polarization and the core-dominance parameter for a certain magnitude:

\[
\rho_{\text{obs}} = k \delta^{3+\eta} 10^{0.4m_{\text{obs}}} = \left( \frac{k}{f} \right) 10^{0.4m_{\text{obs}}} (f \delta^{3+\eta}) = c(m) R \propto R
\]

where \( c(m) = (k/f) 10^{0.4m_{\text{obs}}} \) is a parameter that depends on the magnitude. The relation shows that the high polarization is associated with a large core-dominance parameter.

From the adopted \( c(m) = 0.01, 0.1, 1, \) and 10, several curves are obtained (figure 2); the curves fit the observation data well. The differences in \( c(m) \) are from the differences in the magnitudes amongst the objects. From a catalogue by Hewitt and Burbidge (1993), the maximum magnitude difference among the considered objects is 5 mag, which gives a difference of 100 in \( c(m) \); this value does not conflict with the difference of \( c(m) \) adopted in the present paper, because BL Lacertae objects are variable. The variability of the objects, themselves, should result in a larger than 100 difference in \( c(m) \). In addition, although we used a fixed \( f \) in our discussion, \( f \) is likely to be variable, which would result in a dilution of the correlation (cf. figure 2). Besides, the variation in \( \eta \) would also affect the correlation.

We have tried to separate the data into three subgroups, i.e., the lower \((\Delta m < 2.0 \text{ mag})\), intermediate \((2.0 \text{ mag} \leq \Delta m < 4.0 \text{ mag})\), and higher \((\Delta m \geq 4.0 \text{ mag})\) amplitude variation groups, and found that the higher amplitude variation group shows a better linear relation between the polarization \( P \) and the variation \( \Delta m \). We suspect that because the \( P \) for the sources in this group may be obtained when the sources are bright, they have similar magnitudes \( m \). However, the sample of such a group is small and the statistical significance is very low. More observations in the bright state should confirm the result.

In this work, the correlation between the polarization and the
Table 1. Observation data of BL Lacertae objects.

| Name       | $\Delta m_{\text{Max}}$ | Reference | $P_{\text{Max}}/P_{\text{min}}$ | Reference | $\log R$ | Reference |
|------------|-------------------------|-----------|---------------------------------|-----------|----------|-----------|
| 0048       | 2.7                     | FL99      | 27.1/7.0                        | AS80, CH84| 0.97     | W92       |
| 0118−272   | 1.05                    | FL99      | 18.7                            | SF97      |          |           |
| 0215+015   | 5.0                     | P83       | 20.0/11.9                       | AS80, B86 | 0.90     | W92       |
| 0219+428   | 2.97                    | FL00B     | 18.0/6.0                        | FL99, RS85| 0.25     | W92       |
| 0235+164   | 5.3                     | FL99      | 43.9/6.0                        | ST93, FL96| 2.25     | W92       |
| 0323+022   | 1.3                     | F86       | 10.4/1.0                        | J94       |          |           |
| 0521−365   | 1.4                     | AS80      | 11.0/2.8                        | B83, B86  | 0.01     | W92       |
| 0537−441   | 5.4                     | FL00A     | 18.8/10.1                       | IT90, IT88| 2.3      | G93       |
| 0716+714   | 5.0                     | F97       | 29.0/13.9                       | ST93, RS85| 0.88     | T99       |
| 0735+178   | 4.6                     | FL99      | 36.0/3.0                        | IT90, FL96| 3.4      | W92       |
| 0754+100   | 3.16                    | FL00A     | 26.0/4.0                        | FL99, FL00A| 1.14   | W92       |
| 0818−128   | 3.78                    | FL00A     | 36.0/8.0                        | FL99, FL00A| 0.23   | W92       |
| 0823+033   | 1.41                    | FL00A     | 23.7/3.7                        | IT88, KS90| 0.8      | G93       |
| 0828+493   | 2.0                     | FL99      | 7.9/1.4                         | KS90      |          |           |
| 0829+046   | 3.58                    | FL00A     | 20.5/12.0                       | VW99, CH84| 1.07     | W92       |
| 0851+202   | 6.0                     | F98A      | 37.2/1.0                        | ST93, AS80| 3.5      | W92       |
| 1101+384   | 4.6                     | FL99      | 16.0/0.0                        | T98, RS85 | 1.0      | G93       |
| 1144−397   | 1.92                    | FL99      | 8.5/0.0                         | IT88      |          |           |
| 1147+245   | 0.99                    | FL00A     | 13.0/3.0                        | IM82, IT88| 1.42     | W92       |
| 1215+303   | 3.1                     | FL99      | 14.0/8.0                        | W78, W92  | 0.27     | W92       |
| 1219+285   | 3.13                    | FL00A     | 20.0/2.0                        | E99, RS85 | 3.45     | W92       |
| 1308+326   | 4.17                    | FL00A     | 28.0/0.0                        | ST93, MS81| 1.70     | W92       |
| 1400+162   | 2.8                     | Z81       | 14.0/4.0                        | AS80, CH84| 0.34     | ST        |
| 1418+546   | 4.8                     | FL99      | 24.0/2.0                        | FL99, AS80| 1.77     | W92       |
| 1514−241   | 2.5                     | FL00A     | 8.0/2.0                         | ST93, AS80| 2.41     | W92       |
| 1519−273   | 2.43                    | FL99      | 11.4/5.9                        | IT90, IT88| 0.9      | G93       |
| 1538+149   | 3.7                     | FL99      | 32.8/5.0                        | B86, M90  | 0.95     | W92       |
| 1652+398   | 1.3                     | FL99      | 7.0/2.0                         | CH84, KS90| 1.8      | G93       |
| 1727+502   | 2.1                     | FL99      | 6.0/2.0                         | CH84      | 1.01     | W92       |
| 1749+096   | 2.7                     | FL99      | 32.0/3.0                        | B86, KS90 | 2.83     | W92       |
| 1749+701   | 1.40                    | B90       | 20.3/3.5                        | W92, RS85 | 1.10     | W92       |
| 1807+698   | 2.23                    | FL00A     | 12.0/0.0                        | AS80, KS90| 0.6      | G93       |
| 2155−304   | 1.85                    | FL00B     | 14.2/2.2                        | PE96, B86 | 0.66     | W92       |
| 2200+420   | 5.31                    | F98B      | 23.0/2.0                        | ST93, AS80| 2.41     | W92       |
| 2254+074   | 3.07                    | FL00A     | 21.0/8.8                        | AS80, KS90| 1.77     | W92       |

*References: AS80: Angel, Stockman (1980); B83: Bailey et al. (1983); B86: Brindell et al. (1986); B90: Bozyan et al. (1990); CH84: Cruz-Gonzalez, Huchra (1984); E99: Efimov (1999); F86: Feigelson et al. (1986); F97: Fan et al. (1997); F98A: Fan et al. (1998a); F98B: Fan et al. (1998b); FL96: Fan, Lin (1996); FL99: Fan, Lin (1999); FL00A: Fan, Lin (2000a); FL00B: Fan, Lin (2000b); G93: Ghisellini et al. (1993); IM82: Impey et al. (1982); IT88: Imp, Tapia (1988); IT90: Imp, Tapia (1990); J94: Jannuzi et al. (1994); MS81: Moore, Stockman (1981); M90: Mead et al. (1990); P83: Pettini et al. (1983); PE96: Pesce et al. (1996); SF97: Scarpa, Falomo (1997); ST: see the text; ST93: Stickel et al. (1993); T99: Tian et al. (1999, unpublished); T98: Tosti et al. (1998); VW98: Visvanathan, Wills (1998); W78: Wardle (1978); W92: Wills et al. (1992); Z81: Zekl et al. (1981). We are grateful to the referee for his/her suggestions, comments, and remarks. We thank Dr. B. J. Wills for her sending us a publication. This work is partially supported by the Outstanding Researcher Award of the University of Hong Kong, the Croucher Senior Research Fellowship, the National Natural Science Foundation of China (19973001) and the 973 Project of China (NKBRSF G19990754).
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