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THE DIFFERENCE OF OPTICAL POLARIZATION PROPERTIES BETWEEN XBLs AND RBLs*

XIE GUANG-ZHONG(谢光中)[a)b)c)†], MEI DONG-CHENG(梅冬成)[a)b)c)], and DAI BEN-ZHONG(戴本忠)[a)b)c)]

[a)] *Yunnan Astronomical Observatory, Chinese Academy of Science, Kunming* 650011, *China*

[b)] *The National Astronomical Observatories Chinese Academy of Sciences, Beijing* 100080, *China*

[c)] *Yunnan Astrophysics Center, Yunnan University, Kunming* 650091, *China*

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On the basis of the beaming model, we have derived a relation between the observed polarization ($P^{\rm ob}$) and Doppler-corrected optical magnitude ($m^{\rm corr}$), $\log P^{\rm ob} = 0.4(1-k)m^{\rm corr} + C$. We tested the correlation between $P^{\rm ob}$ and $m^{\rm corr}$. The main results are as follows: (1) for both high and low states, there are strong correlations between $P^{\rm ob}$ and $m^{\rm corr}$ for 29 RBLs with well-observed polarization and Doppler factor, where $m^{\rm corr} = m^{\rm ob} + (3+\alpha)\log\delta/0.4$, and δ is the optical Doppler factor; (2) no correlation exists between $P^{\rm ob}$ and the observed optical magnitude, $m^{\rm ob}$, for the 29 RBLs in high state, but there is a close correlation for the 29 RBLs in low state; (3) however, there is an obvious anti-correlation between $P^{\rm ob}$ and $m^{\rm corr}$ for 35 XBLs with good simultaneous observation data. Our results show that (i) a new difference in polarization is found between RBLs and XBLs; (ii) this difference in polarization between RBLs and XBLs seems really to be physical differences.

Keywords: BL Lac objects, polarization, beaming effect
PACC: 9850, 9870

I. 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, core-dominated non-thermal continuum. Some of BL Lacertae objects show superluminal motion and high gamma-ray emissions.[1−6] According to surveys, BL Lacertae objects can be classified as X-ray selected BL Lac objects (XBLs), if their $\alpha_{\rm RX} < 0.75$[7] or 0.8[8], otherwise they are classified as radio-selected BL Lac objects (RBLs).

The relationship between BL Lac objects and flat spectrum radio Quasars (FSRQs) is of great interest. Sambruna *et al.*[8] found from the spectral energy distributions that three subclasses of blazars have different but essentially continuous properties: XBLs and FSRQs occupy separate regions in broadband colour-colour diagrams, while RBLs bridge the gap between the two populations.

Two alternative interpretations have been proposed to explain those results: (1) the 'orientation hypothesis', which states that the differences in luminosity and spectra result from relativistic beaming effects with the jets of XBLs being observed with larger angles with respect to the line of sight than those of RBLs[9]; (2) the real difference physics, which states that the differences between RBLs and XBLs must be attributed, at least in part, to real physical differences.[8] For blazars, their spectral energy distributions show double-peak structure (the lower and higher frequency peaks). The lower frequency part is generally considered to be produced by synchrotron radiation of relativistic electrons in the jet while the higher energy part is usually considered to be produced by Compton upscattering of these same electrons. In the spectral energy distributions of XBLs, the X-ray emission comes from the high-energy end of the synchrotron emission, whereas in that of RBLs, the X-ray emission is from inverse-Compton scattering.

Besides, the γ-ray observations also support the hypothesis that the differences between XBLs and RBLs are physical. In fact, out of the over 60 blazars detected by EGRET in the 100 MeV range, only two objects (Mrk421,PKS2155-304) are XBLs. But BL Lac objects detected at TeV are all XBLs. They are Mrk421, Mrk501[10],2344+514, PKS2155-304 and 1ES2005-489. These new observations show that the radiation mechanism of blazars is very complicated and should be studied intensively.

The observed properties of RBLs are systemati-

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†E-mail: gzxie@public.km.yn.cn

cally different from those of XBLs. The latter have flatter spectral energy distribution from the radio through X-rays, a higher starlight fraction, a higher observed peak of emitted power from radio through X-ray spectral energy distribution, and convex optical to X-ray continua. Furthermore, XBLs show lower polarization as compared with RBLs. They occupy different regions in effective spectral index $\alpha_{\rm RO}$–$\alpha_{\rm OX}$ plot.[11–13]

In 1997 and 1999, Fan *et al.*[14,15] reported that they found a correlation between observed polarization ($P^{\rm ob}$) and the optical magnitude ($m^{\rm ob}$) for these BL Lac objects (RBLs+XBLs) with the Doppler factor. In 1999, Cheng, Fan and Dai applied this relation to the polarization of Gamma-Ray-Burst (GRBs) [16]. But the observations show that the polarization in Mkn421 is correlated with the brightness of the source,[17] that is, the observation results in X-ray selected BL Lac object, Mkn421, imply that it seems to be an anti-correlation between $P^{\rm ob}$ and $m^{\rm ob}$ for XBLs, rather than a correlation.

It is known that the observed properties of XBLs are systematically different from those of RBLs. Particularly, XBLs show lower polarization as compared with RBLs. It is natural for one to think that the large difference in polarization properties between RBLs and XBLs comes from the difference in the beaming effects and, if so, there should be different correlations between those properties for RBLs and XBLs.

In this paper, we will investigate these new correlations quantitatively for RBLs and XBLs, in terms of the relativistic beaming model. In section II, the new relation for the polarization and the Doppler-corrected magnitude is derived in terms of the relativistic beaming model of BL Lac objects. The descriptions of samples of RBLs and XBLs are given in section III, and the different correlation analysis is made in section IV. The discussion and conclusions will be given in section V.

II. MODEL

Here we follow the idea of the beaming models.[18,14,19] The observed flux, $S_j^{\rm ob}$, of a relativistic jet is related to its intrinsic flux, $S_j^{\rm in}$, by $S_j^{\rm ob}$=$\delta^n S_j^{\rm in}$, where δ is defined by $\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$, β is the velocity in units of speed of light,$\Gamma = (1-\beta^2)^{-\frac{1}{2}}$ is the Lorentz factor, θ is the viewing angle. The value of n depends on the shape of the emitted spectrum and the detailed physics of the jet,[19] $n = 3+\alpha$ is for a moving sphere and $n = 2+\alpha$ is for the case of continuous jet, where α is the spectral index. For a two-component model,[14] the total flux of a source, $S^{\rm ob}$ is the sum of an unbeamed part $S_{\rm unb}^{\rm ob}$ and a jet flux $S_j^{\rm ob}$,

$$S^{\rm ob} = S_{\rm unb} + S_j^{\rm ob}, \tag{1}$$

where $S_j^{\rm ob} = \delta^n S_j^{\rm in}$. Assuming $S_j^{\rm in} = fS^{\rm unb}$,[20] we have $S^{\rm ob} = (1+f\delta^n)S_{\rm unb}$. In general, the flux is not totally polarized in the jet flux, and it is reasonable to assume that the jet flux consists of two parts, namely, the polarized (S_{jp}) and unpolarized (S_{jup}),i.e.,

$$S_j^{\rm in} = S_{jp} + S_{jup}. \tag{2}$$

From Eqs.(1) and (2), we have

$$S_j^{\rm ob} = \delta^n(S_{jp} + S_{jup}) = \delta^n S_{jp} + \delta^n S_{jup}. \tag{3}$$

Then the observed optical polarization can be expressed as

$$P^{\rm ob} = \frac{\delta^n S_{jp}}{S^{\rm ob}}. \tag{4}$$

From Eqs.(1)–(3), we can see that the polarized jet flux (S_{jp}) is a variable in general. From relation (4), we can obtain following relation

$$P^{\rm ob} = \frac{S_{jp}}{A}\delta^{3+\alpha}10^{0.4{\rm m}^{\rm ob}}, \tag{5}$$

where $m^{\rm ob}$ is the observed magnitude, α is the optical spectral index, δ is the optical Doppler factor which can be estimated from optical variation observations.[20] Unfortunately, we do not know S_{jp}, since it is not a constant, but we can represent it as

$$S_{jp} = B10^{-0.4m_{\rm e}}, \tag{6}$$

where $m_{\rm e}$ is an equivalent magnitude. Now, from relation (5), we have

$$\begin{aligned} P^{\rm ob} &= C10^{-0.4m_{\rm e}}10^{0.4(m^{\rm ob}+\frac{n}{0.4}\log\delta)} \\ &= C10^{-0.4m_{\rm e}}10^{0.4m^{\rm corr}}, \end{aligned} \tag{7}$$

where

$$m^{\rm corr} = m^{\rm ob} + \frac{n}{0.4}\log\delta, \tag{8}$$

which we have obtained in 1991.[20] It is the Doppler-corrected magnitude, $m^{\rm corr}$, that is, the intrinsic magnitude. From Eqs.(7) and (8), if we assume that the Doppler-corrected magnitude $m^{\rm corr}$ and the equivalent magnitude $m_{\rm e}$ is related by a simple form

$$m_{\rm e} = km^{\rm corr}, \tag{9}$$

we have

$$\log P^{\rm ob} = 0.4(1-k)m^{\rm corr} + C_1, \qquad (10)$$

where C_1 is a constant. This is the relation between the polarization and the $m^{\rm corr}$ we derived. Because the flux $S^{\rm in}_{jp}$ must be smaller than the flux $S^{\rm corr}$, m_e will be larger than $m^{\rm corr}$ and $k > 1$, that is, $\log P^{\rm ob}$ is anti-correlation with $m^{\rm corr}$.

III. THE SAMPLES OF RBLs AND XBLs

In order to avoid the selected effects, our sample of RBLs consists of all the RBLs of Fan's sample.[14] But the Doppler factors of some sources have been corrected or determined by new observed data in recent years. The relevant data are listed in Table 1 with the following headings: column 1 gives the name of the source; column 2, the maximum optical polarization; column 3, the references to column 2; column 4, the optical magnitude in high state; column 5, the references to column 4; column 6, the Doppler-corrected magnitude in high state which is obtained from relation (8); column 7, the optical magnitude in low state; column 8, the references to column 7; column 9, the Doppler-corrected optical magnitude in low state; column 10, the optical spectral index; column 11, the references to column 10; column 12, the optical Doppler factors and the radio Doppler factors indicated by $\star$; column 13, the references to column 12. It should be pointed out that some Doppler factors (13 sources) are radio Doppler factors. We use the relation $\delta_R \sim \delta^{1.5}$ shown in Ref.[21] to calculate the optical Doppler factor, which is good for BL Lac objects and other AGNs.[14,22]

Our sample of XBLs consists of all sources with maximum polarization (unfiltered) observed and m_v which have been given by Jannuzi, Smith and Elston in 1994[11] and 1993[23] (35 sources). Most of them have simultaneously observed polarization (unfiltered) and m_v. They are listed in Table 2: column 1 gives the name of the source; column 2, the maximum optical polarization; column 3, the observed optical magnitude; column 4, the optical Doppler factors from Ref.[24]; column 5, the Doppler-corrected optical magnitude which obtained from relation (8).

IV. THE CORRELATION ANALYSIS

Table 1. Radio selected BL Lac objects sample.

Source (1)	$P_{\rm ob}$ (2)	Ref. (3)	$m_v^{\rm ob}(1)$ (4)	Ref. (5)	$m_v^{\rm corr}(1)$ (6)	$m_v^{\rm ob}(2)$ (7)	Ref. (8)	$m_v^{\rm corr}(2)$ (9)	α (10)	Ref. (11)	δ (12)	Ref. (13)
0048–097	27.1	[5]	15.42	[34]	21.54	17.0	[5]	23.54			10.5$\star$	[4]
0215+015	20	[1]	14.5	[35]	19.4	19.5	[20]	24.4	1.8	[20]	2.56	[20]
0219+428	18	[31]	15.2	[34]	20.3	16.6	[20]	21.7	1.3	[20]	2.99	[20]
0235+164	43.9	[5]	15.5	[34]	20.5	19.5	[20]	24.5	2.5	[20]	2.19	[20]
0300+471	24.0	[5]	17.2	[34]	21.3	20.0	[1]	22.1			4.8$\star$	[4]
0316+413	6.0	[1]	11.9	[1]	11.9	12.48	[34]	12.48	1.54	[20]	$1.0^{(1)}$	
0454+844	18.5	[14]	16.5	[5]	19.7	18.0	[35]	21.22			3.7$\star$	[4]
0521–365	11	[32]	14.5	[36]	14.5	16.8	[20]	16.8	1.5	[20]	3.3$\star$	[4]
0537–441	18.7	[5]	16.4	[37]	20.0	16.5	[34]	20.1	1.0	[37]	2.28	[20]
0735+178	36.0	[14]	13.4	[35]	19.9	17.0	[20]	23.5	1.27	[20]	7.3$\star$	[4]
0754+100	26.0	[14]	14.5	[35]	20.2	16.3	[20]	22.0	1.1	[20]	3.56	[20]
0823+033	22.9	[5]	16.8	[37]	20.0	18.0	[5]	21.4			3.7$\star$	[4]
0851+202	37.2	[5]	14.0	[35]	19.1	16.6	[40]	21.7	1.2	[40]	3.08	[6]
0954+658	33.7	[5]	16.7	[5]	20.9	17.5	[3]	21.7			5.0$\star$	[4]
1156+295	9.0	[1]	14.41	[34]	16.5	15.6	[1]	18.1	1.0	[6]	1.8	[6]
1219+285	20.0	[33]	16.5	[36]	18.0	17.0	[20]	18.5	1.6	[20]	1.35	[20]
1308+326	28.0	[5]	15.2	[34]	19.3	19.0	[20]	23.1	1.5	[20]	6.8$\star$	[4]
1514–241	8.0	[5]	15.0	[36]	16.2	16.7	[20]	17.9	1.5	[20]	1.26	[20]
1519–273	11.4	[5]	17.9	[37]	20.4	18.5	[5]	21.0			$2.78^{\star(2)}$	
1538+149	29.6	[5]	15.5	[35]	18.0	17.3	[34]	19.8			1.3$\star$	[4]
1749+096	32.0	[5]	15.57	[29]	19.85	17.34	[29]	21.62			2.68	[20]
1749+701	20.3	[3]	16.5	[5]	16.9	17.0	[35]	17.4			1.1$\star$	[4]
1803+784	35.2	[5]	16.4	[38]	22.0	17.0	[38]	22.7			8.5$\star$	[4]
1807+698	12.0	[1]	14.2	[38]	15.3	15.1	[20]	16.2	1.5	[20]	1.24	[20]
2007+777	15.1	[5]	16.5	[35]	20.5	17.0	[38]	21.0			4.7$\star$	[4]
2200+420	23.0	[5]	14.5	[39]	16.1	17.7	[20]	18.1	2.3	[20]	1.3	[6]
2223–052	17.0	[1]	17.9	[35]	23.1	18.6	[20]	23.1	1.0	[20]	3.3	[25]
2251+158	16.0	[1]	16.1	[34]	22.1	16.1	[34]	22.1	1.0	[34]	3.79	[25]
2254+074	21.0	[1]	16.5	[35]	19.4	17.33	[20]	20.2	2.6	[20]	1.61	[20]

(1) The optical Doppler of 0316+413 is taken as 1.0. (2) The radio Doppler factor of 1519–273 is calculated by the formula in Ref.[4], but the X-ray flux is taken from Ref.[41].

We have calculated $m^{\rm corr}$ using formula (8), in which $n = 3 + \alpha$ is assumed, because the calculations of the Doppler factor in our previous paper[20] have chosen $n = 3 + \alpha$. The results are also listed in Tables 1 and 2. Using the data in Table 1, we have made the correlation analysis. The main results are as follows:

Table 2. X-ray selected BL Lacs sample.

Source	$P_{\rm ob}$	$m_v^{\rm ob}$	δ	$m_v^{\rm corr}$
(1)	(2)	(3)	(4)	(5)
0122+0903	6.25	20.07		20.1
0158+0019	3.1	18.6		18.6
0205+3509	1.91	19.27		19.3
0257+3429	6.25	18.61		18.61
0317+1843	3.99	18.13	1.21	18.6
0323+022	10.01	16.13	1.0	16.13
0419+1943	2.90	20.26		20.3
0514+064	6.91	19.01		19.01
0548–322	3.21	15.5	1.72	17.9
0607+7108	4.28	19.6		19.60
0737+7441	2.70	17.06		17.06
0922+7459	6.0	20.02		20.02
0950+4929	5.19	18.22		18.22
1101–232	1.33	18.35		18.35
1219+305	5.02	15.90	1.0	15.9
1221+2452	11.86	17.34		17.34
1229+6430	1.04	17.47		17.47
1235+6315	2.62	18.83	1.0	18.83
1402+0416	9.52	17.14	1.0	17.14
1407+5954	8.64	19.56		19.6
1415+2557	7.53	17.08		17.1
1462+428	2.35	16.51		16.51
1458+2249	7.03	16.67		16.7
1534+0148	3.55	18.73		18.7
1552+2020	5.95	17.32		17.3
1652+398	3.61	13.60	2.11	16.9
1704+6046	3.10	19.86		19.9
1722+119	15.54	15.47		15.5
1757+7034	3.70	18.27		18.3
2143+0704	10.83	18.05	1.0	18.1
2154–304	10.80	13.08	1.0	13.1
2336+0517	5.13	19.53		19.5
2342–1531	5.33	19.81		19.8
2347+1942	3.09	19.93		19.9

1. No correlation exists between $\log P^{\rm ob}$ and $m^{\rm ob}$ in the high state for 29 RBLs (see Fig.1), but there is a correlation between $\log P^{\rm ob}$ and $m^{\rm ob}$ in low state for 29 RBLs (see Fig.2). The linear regression equation is

$$\log P_{\rm max}^{\rm ob}(\%) = 0.08349 m_v^{\rm ob} - 0.1382, \qquad (11)$$

and a coefficient $\gamma = 0.55$ is obtained with a chance probability of $p = 2.6 \times 10^{-3}$.

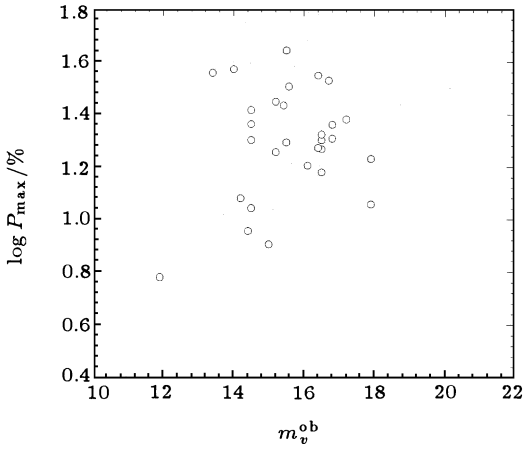


Fig.1. The polarization log $P(\%)$ against the observed magnitude $m_v^{\rm ob}$ of 29 RBLs in high state.

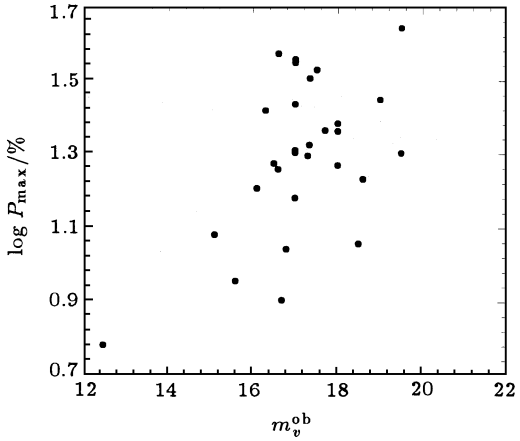


Fig.2. The polarization log $P(\%)$ against the observed magnitude $m_v^{\rm ob}$ of 29 RBLs in low state.

2. A strong correlation exists between $\log P^{\rm ob}$ and $m_v^{\rm corr}$ in the high state for 29 RBLs (see Fig.3). The linear regression equation is

$$\log P_{\rm max}^{\rm ob}(\%) = 0.05043 m_v^{\rm corr} + 0.3374, \qquad (7)$$

and a larger coefficient $\gamma = 0.60$ is obtained with a chance probability of $p = 8.7 \times 10^{-4}$.

3. A very strong correlation exists between $\log P^{\rm ob}$ and $m^{\rm corr}$ in the low state for 29 RBLs. The linear regression equation is

$$\log P_{\rm max}^{\rm ob}(\%) = 0.05551 m_v^{\rm corr} + 0.15441, \qquad (13)$$

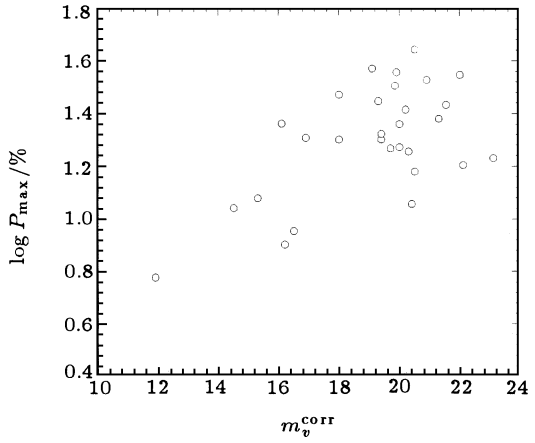


Fig.3. The polarization $\log P(\%)$ against the Doppler-corrected magnitude m_v^{corr} of 29 RBLs in high state.

and a much larger coefficient $\gamma = 0.72$ is obtained with a chance probability of $p = 2.5 \times 10^{-5}$. Obviously, Eq.(10) is a very important relation (see Fig.4).

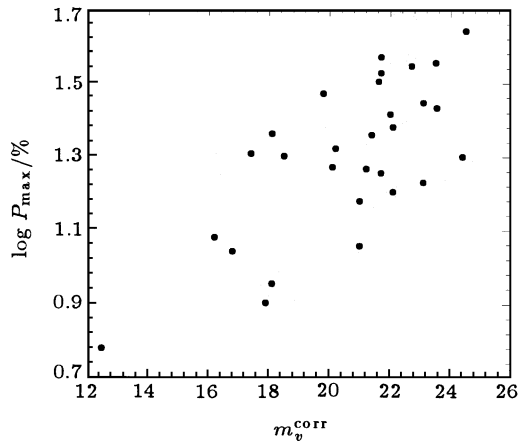


Fig.4. The polarization $\log P(\%)$ against the Doppler-corrected magnitude m_v^{corr} of 29 RBLs in low state.

4. From the linear regression Eqs.(11) and (12), we can obtain k=0.852 (for high state of RBLs) and k=0.866 (for low state of RBLs). Now, we can estimate the polarized jet flux, S_{jp}, from Eq.(6).

5. For the analysis of the difference between RBLs and XBLs, we can study the correlation mentioned above for XBLs. It is known that XBLs are not so strongly beamed and the observed data can be taken as the Doppler-corrected ones for unknown Doppler factor objects[25,26]. Using the data listed in Table 2, the linear regression equation is

$$\log P_{max}^{ob}(\%) = -0.05529 m_v^{corr} + 1.67252, \qquad (14)$$

and a significant anti-correlation coefficient of $\gamma = -0.33$ is obtained with a chance probability of $p = 3.8 \times 10^{-2}$. Obviously, this is a very interesting result, which is displayed in Fig.5. We get k=1.138. From the above analysis, we find that there are substantial differences in optical polarization properties between XBLs and RBLs; therefore, we must study the optical polarization properties that separate XBLs from RBLs.

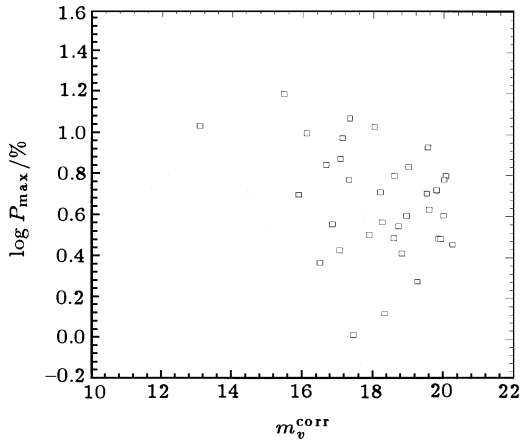


Fig.5. The polarization $\log P(\%)$ against the Doppler-corrected magnitude m_v^{corr} of 35 XBLs.

V. DISCUSSIONS

It is known that the observational properties of RBLs are systematically different from those of XBLs. The latter have flatter spectral energy distribution from the radio through X-ray region, a higher starlight fraction, a higher observed peak of the emitted power from radio through X-ray spectral energy distribution and convex optical to X-ray continua. Furthermore, they occupy different regions in the effective spectral index plot.[8,11,13,27,28] XBLs show lower polarization and lower beam effect as compared with RBLs. Our results in this paper reveal a new observational difference between XBLs and RBLs, which indicates that the polarization is correlated with the Doppler-corrected optical magnitude for RBLs, but the polarization is anti-correlated with the Doppler-corrected magnitude for XBLs. However, relation (10) derived from the beaming model shows that the polarization is anti-correlated with the Doppler-corrected magnitude; that is, the beaming model cannot explain the polarization properties of RBLs.

In 1989, Szuszkiewicz *et al.* reported that the optical polarization in 1215+303 is strongly correlated with the intensity. Recently, Tosti *et al.*[17] also found that a clear correlation exists between the variations of polarization and brightness during the Mkn421 1997 outburst. Obviously, the observed results for both 1215+303 and Mkn421 are consistent with our results that the polarization is anti-correlated with the intrinsic magnitude for XBLs. Because both 1215+303 and Mkn421 are XBLs.

Our results in section IV indicate that the calculated correlation between $P^{\rm ob}$ and $m_v^{\rm corr}$ is better in low state than that in high state for RBLs ($\gamma = 0.72$ for low state and $\gamma = 0.60$ for high state). The observations of RBLs are also consistent with our correlation analysis results. For instance, the light curve of 3C66A in 1989 shows that it has an outburst of 0.46 mag/32 min and a very rapid decline of 0.52 mag/10 min.[29] A similar phenomenon was observed from OT081.[29] It is known that the rapid variability corresponds to large Doppler factors.[20] On the other hand, the observations show that the polarization angle in OJ287 (RBL) in the optical region changed very rapidly in the faintest state.[30] It is well known that the low state represents the quiescent state of the sources, and the high state represents outburst phases of the sources. On the basis of the astrophysical theory, the outbursts were created by very complicated physical processes, such as, varieties of instability. Our results for RBLs in this paper probably show that the low state represents the more realistic case of the continuous jet of the source. However, the observed sample is small. More simultaneous observations for RBLs and XBLs are necessary.

Our results show that the polarization of XBLs is weakly correlated with the beaming effect, but the beaming effect cannot explain the new difference in polarizations between RBLs and XBLs. The new difference between RBLs and XBLs seems to be real physical difference. Perhaps, XBLs have smaller polarization than of RBLs. In general, the polarization is dependent on the degree of ordering of the magnetic field in the synchrotron emission regions. It is known that the beaming effect of RBLs is strong and that of XBLs is very weak and can be neglected. Therefore, the polarization of RBLs is not consistent with the relation (10) derived from the beaming model and the polarization of XBLs seems consistent with the relation (10). Our conclusion is that the polarization of BL Lac objects is not related to the beaming effect.

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