Astron. Astrophys. 327, 947–951 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Polarization and beaming effect for BL Lacertae objects

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Received 30 January 1997 / Accepted 11 June 1997

Abstract. We derive a relation between the observed polarization and beaming factor (Doppler factor) and compare this relation with the observed data for BL Lac objects. Our results indicate that the high optical polarization is correlated to the beaming effect and the difference in polarizations between X-ray selected (XBLs) and radio selected (RBLs) BL Lac objects is due to the difference in their beaming effects.

Key words: BL Lac objects – galaxies: jets-radio continuum: galaxies – polarization

1. Introduction

BL Lac objects are generally described as a subclass of active galactic nuclei(AGNs). Hewitt & Burbidge (1993) designate 90 sources in their catalog as BL Lac objects. Veron-Cetty & Veron (1996) and Padovani & Giommi (1995a) list 220 and 233 BL Lac objects in their catalogs respectively. BL Lac objects are always radio-loud and highly polarized objects characterized by weak or absent line feature. Some of them are core-dominated radio sources displaying superluminal motion, variability and gamma-ray loud (Angel & Stockman 1980; Zensus 1989; Vermeulen & Cohen 1994; Ghisellini et al 1993; Fan et al 1996a; Fichtel et al 1994; von Montigny et al 1995; Thompson et al 1993, 1995, 1996; Lin 1996; Quinn et al 1996). According to the surveys, BL Lac objects are divided into radio-selected BL Lac objects (RBLs) and X-ray selected BL Lac objects (XBLs). But some so-called RBLs have been observed in the ROSAT all sky survey and the *Einstein* Slew Survey (Perlman et al. 1996). For these BL Lac objects, their classification can be made by their relative fluxes at radio and X-ray frequencies, α_{rx}. They are classified as XBLs if their $\alpha_{rx} < 0.75$ (Urry & Padovani 1995) or 0.80(Sambruna et al. 1996), otherwise they are classified as RBLs. Complete radio flux-limited samples have been compiled for RBLs (Kuhr & Schmidt, 1990; Stickel et al. 1991). A complete X-ray-flux-limited sample of BL Lac objects (XBLs) has also been compiled from the Einstein Extended Medium Sensitivity Survey (EMSS) (Gioia et al 1990; Morris et al 1991; Stocke et al 1990).

The properties of RBLs are systematically different from those of XBLs. The latter have flatter spectral energy distribution from radio through X-ray (Ledden & O'Dell 1985), a higher starlight fraction (Morris et al 1991), a higher observed peak of the emitted power from radio through X-ray spectral energy distribution (Giommi et al 1995) and convex optical-to-X-ray continua (Sambruna et al 1996). XBLs fit the Hubble diagram much better than RBLs (Burbidge & Hewitt 1987; Fan et al 1994) and show good correlations between X-ray, optical magnitude, and radio flux while RBLs do not (Maccagni et al 1989; Fan et al 1993; 1994). RBLs and XBLs occupy different places not only in the $\alpha_{ro} - \alpha_{ox}$ diagram (Schwartz et al 1989; Stocke et al 1989; Tagliaferri et al 1989) but also in the α_{rx}–α_{ox} and α_{ro}–α_{rx} diagrams (Fan & Xie 1996). On the other hand, the radio and optical luminosities for RBLs are higher than those for XBLs, but the X-ray luminosities are almost the same for the both (Maraschi et al 1989; Urry et al 1991; Laurent-Muehleison et al 1993). XBLs generally have lower optical polarization (Jannuzi et al 1993a,b; 1994) with an average polarization $P_{opt} < 5\%$ (except for 1722+119, Brissenden et al 1990), while RBLs have an average optical polarization $P_{opt} > 10\%$.

Some arguments have been proposed to explain the differences between RBLs and XBLs. First, the location of the high energy cutoffs of the synchrotron emission for XBLs is suggested, which can explain why XBLs have relatively lower ratios of radio-to-X-ray flux (Giommi & Padovani 1994, Kollgaard 1994). Second, XBLs are intrinsically less luminous which can explain the extended power difference (Padovani & Giommi 1995b). However, the most natural way to explain the differences between RBLs and XBLs is the relativistic beaming model proposed by Blandford & Rees (1978) and developed by others (Blandford & Konigl 1979; Marscher & Gear 1985), in which RBLs and XBLs are the same objects seen from different directions (Celotti et al 1993; Urry 1989; Urry & Padovani 1991; Urry et al 1991; Fan & Xie 1996). The milder radio-optical properties of XBLs are generally attributed to a larger angle between

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the jet and the line of sight, while the similar X-ray luminosities lead to the suggestion that the X-ray beam is broader than the radio and optical beams (Maraschi et al 1986; Padovani & Urry 1990; Sambruna et al 1996). Kollgaard (1994) argued that the different properties of XBLs and RBLs can be explained in terms of the accelerating jet model (Ghisellini & Maraschi 1989) where the X-rays arise from the region of the jet closer to the core than that of the radio emission. The X-rays are subject to less beaming and so are detected over a wider range of angle than that of the radio emission. This accelerating model has gained support from the obtained Lorentz factors $< \Gamma_x >\sim 3$ (Padovani & Urry 1990) and $< \Gamma_r >\sim 7$ (Urry et al. 1991) and has been used to discuss the differences between RBLs and XBLs in luminosities, spectral indices, and the multifrequency correlations.

Recently, from the spectral energy distribution, Sambruna et al. (1996) proposed that the homogeneous and inhomogeneous jet models cannot explain the different energy distribution. It follows that the orientation effect alone is not sufficient to turn an XBL into a RBL. Instead, the full range of observed spectral energy distribution can be accounted for by a change of intrinsic parameters, such as magnetic field, jet size, and the maximum electron energy. But this argument does not imply that the average beaming factor and viewing angles of XBLs and RBLs should be the same. In fact, the beaming factor itself maybe an additional intrinsic difference between RBLs and XBLs (Sambruna et al. 1996).

Since the beaming factor may be an additional intrinsic difference between XBLs and RBLs, and the beaming effect has been used to discuss the difference between XBLs and RBLs in luminosities, spectral indices, and the multiwavelength correlations, we propose to use it to discuss the difference in polarization between RBLs and XBLs.

2. Polarization of BL Lac objects

2.1. Relation

We follow the idea of the jet models (Urry & Padovani 1990, Padovani & Urry 1990). The observed flux, S_j^{ob}, of a relativistic jet is related to its intrinsic flux, S_j^{in}, by $S_j^{ob} = \delta^p S_j^{in}$, where δ, the Doppler factor of the jet, is defined by $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$, β is the velocity in units of the speed of light, $\Gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor, and θ is the viewing angle. The value of p depends on the shape of the emitted spectrum and the detailed physics of the jet (Lind & Blandford 1985), $p = 3+\alpha$ is for a moving sphere and $p = 2+\alpha$ is for the case of a continuous jet, where α is the spectral index. We consider a two-component model in which the total flux of a source, S^{ob}, is the sum of an unbeamed part S_{unb} and a jet flux $S_j^{ob} = \delta_p S_j^{in}$. Assuming that the intrinsic flux of the jet is some fixed fraction f of the unbeamed flux, $S_j^{in} = f S_{unb}$ (Urry & Shafer 1984), we have $S^{ob} = (1 + f\delta_p)S_{unb}$. The direction of the magnetic field in the jet should in general, be random except for some of it along the direction of the jet. So if the flux is not totally polarized, and it is not unreasonable to assume that the jet flux consists of polarized and unpolarized parts and which are proportional to each other, namely $S_j^{in} = S_{jp} + S_{jup}$, $S_{jp} = \eta S_{jup}$, where η is a coefficient which determines the polarization of the emission in the jet, then the observed optical polarization can be expressed as

$$P_{ob} = \frac{(1+f)\delta_o^p}{1+f\delta_o^p} P_{in} \quad , \tag{1}$$

where intrinsic polarization is defined by

$$P_{in} = \frac{f}{1+f}\frac{\eta}{1+\eta} \quad , \tag{2}$$

and δ_o is the Doppler factor in the optical band. It is clear that $P_{ob} = P_{in}$ for $\delta_o = 1$. If P_{in} is a constant for the same class of sources, then there should be a correlation between the Doppler factor and the observed polarization. From the expressions (1) and (2), two parameters, f and η, must first be determined in order to give P_{in}. In general, the condition of $P_{in} < f$ must be satisfied from equation (2).

2.2. Observed polarization and Doppler factor

The relevant data are listed in Table 1. Col. 1 gives the name of the source, Col. 2 the classification, Col. 3 the redshift, Col. 4 the maximum optical polarization, Col. 5 the references to Col. 4, Col. 6 the radio Doppler factor from the paper of Ghisellini (1993), Col. 7 the optical Doppler factor from the paper of Xie et al (1991). The object 0521-365, which is classified as an RBL in our paper, is classified as an XBL by other authors (Remero et al 1995). However, its optical spectral index of $\alpha_{IR-UV} = 1.43 \pm 0.09$ (Pian et al. 1994) is in the range of the spectral indices of RBLs, $< \alpha_o >= 1.05 \pm 0.42$ (Falomo et al. 1994). So, we believe that it should be classified as an RBL. For 0716+714, its violent optical variation of $m = 4^m.0 - 5^m.0$(Qian et al. 1995) is similar to that of typical RBLs (0851+202, 1215+285 (Cruz-Gonzales & Huchra 1984), its quasi-simultaneous radio, optical and X-ray data give $\alpha_{radio-optical-X-ray} = 1.0$, which is in the range of the optical spectral indices of RBLs (Falomo et al. 1994) and satisfies $\alpha_{rx} > 0.8$. So, although it has been observed in ROSAT all sky survey, we still classify it as an RBL. It should be pointed out that the radio Doppler factors given by Ghisellini (1993) are the lower limits of the Doppler factor δ_{sph}, which are estimated from the SSC model with $p = \alpha + 3$ in the case of a spherical region of observed angular diameter. In the continuous jet model with $p = 2 + \alpha$, the Doppler factor, δ_{jet}, can be estimated by $\delta_{jet} = \delta_{sph}^{(4+2\alpha)/(3+2\alpha)}$ (Ghisellini 1993, Urry & Padovani 1995), and $\alpha = -0.3$ is used (Padovani & Urry 1992, Urry et al 1991). We consider two cases. First, we use the radio Doppler factors to deduce the optical Doppler factors by using $\delta_r = \delta_o^{1.5}$ (Fan et al 1993) if the optical Doppler factor is not available. The observed data for the spherical model and the continuous jet model are shown in Figs.1 and 2 (the open circles stand for RBLs and the filled circles for XBLs). Second, radio Doppler factors for some BL Lac objects listed in Table 1 have also been obtained by Schwartz & Ku (1982): $\delta_r = 8.8$ for 0048-097, 28.0 for 0235+164, 3.7 for 0735+178, 3.6 for 0754+100, 35.0 for 0851+202, 1.6 for 1219+285, 32.0 for 1308+326 and 3.8 for 1538+149. $\delta_r \geq 10.0$ for 0215+015 has been obtained by Kikuchi(1988). If we choose these alternative radio Doppler factors for these objects to estimate their corresponding optical Doppler factors and, for other objects, the Doppler factors in table 1 are used. Similar results as in Figs 1 and 2 can be obtained.

We want to remark that it is reasonable to use the relation of $\delta_r = \delta_o^{1.5}$. In fact, Ghisellini & Maraschi (1989) proposed that the bulk velocity of the plasma increases with increasing distance from the core and synchrotron X-rays are weakly beamed, while optical and radio emissions are more strongly beamed. This model seems to have got support from the results $< \Gamma_x >= 3$ and $< \Gamma_r >= 7$ (Padovani & Urry 1990, Urry et al 1991). Based on this accelerating model, we assume that the Doppler factor satisfies the expression $\delta_\nu \sim \delta_o^{1+\frac{1}{8}log(\nu_o/\nu)}$. Therefore, the X-ray, optical and radio Doppler factors are correlated and any two of them will be known if the other one is known, since $\delta_r = \delta_o^{1.5}$ and $\delta_x = \delta_o^{0.5}$ (Fan et al 1993). When this relation is used, the corrected data of RBLs show much better multiwavelength correlations (Fan et al 1993) and they satisfy the same relation as that of XBLs (Fan & Xie 1996). This Doppler expression is also adapted to Seyfert galaxies (Xie et al 1995) and OVV/HPQs (Fan 1997), and has been confirmed (Fan et al 1996b) to be a good approximated expression from the superluminal motion (Vermeulen & Cohen 1994, Fan et al. 1996a).

2.3. Comparison with observations

In order to compare our relation with the observed data. Two parameters, f and η, must first be determined. The parameter f is the ratio of the intrinsic luminosity of the jet to the unbeamed luminosity and its possible value is from 0.001 to 1.0 (Padovani & Urry, 1990, 1991; Urry et al. 1991; Urry & Padovani 1995). The parameter η is chosen to be 0.6, which means polarization in the jet is about 38%. We show comparisons of our results with the observed data for the spherical model and continuous jet model in Figs. 1 and 2 (here $\alpha = 1.0$), where $f = 0.001$, 0.01, 0.1 and $\eta = 0.6$ have been used, which correspond to $P_{in} = 0.038\%$, 0.38%, 3.4% respectively. On the other hand, it is obvious that the observed optical polarization is not obtained simultaneously with the Doppler factor. In order to reduce this effect, one can choose the maximum optical polarization and the largest optical Doppler factors to compare with the theoretical curves.

Our results in Figs. 1 and 2 show that the polarization increases with the increasing Doppler factor and tends to a constant as the Doppler factor increases. That means that the total flux will be dominated by the emission from the jet with high Lorentz factor and then the observed polarization should be determined by the polarization within the jet. Therefore, we should observe similar polarizations if the polarization in the jet is the same for a single class, which can explain the difference in polarizations between XBLs and RBLs since XBLs are weakly beamed (Padovani 1992; Perlman & Stocke 1993) while RBLs are strongly beamed. But it can be seen that there are some scattering points, which may result from (i) the radio Doppler factors are a lower limit, (ii) the maximum optical polarization and the Doppler factors are not obtained simultaneously, (iii) the polarization in the jet is not the same, especially for 1519-273, and (iv) the maximum polarization has not been obtained for some objects because BL Lac objects do not spend much time at polarization as high as 30% (Jannuzi et al 1994). Comparing Figs. 1 and 2, it seems that the data points in Fig. 2 fits the theoretical curves better than those in Fig. 1, which supports the idea that the continuous jet model is a more realistic case.

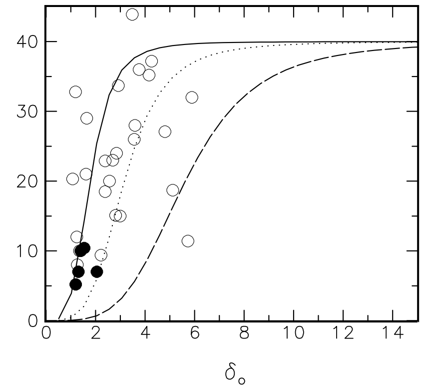

Fig. 1. The relation between optical polarization and optical Doppler factor in the spherical model, which implies $p = 3 + \alpha$ with $\alpha = 1.0$ for RBLs (open circles) and XBLs (filled circles). The dashed curve stands for $f = 0.01$, the dotted curve for $f = 0.01$ and the solid curve for $f = 0.1$.

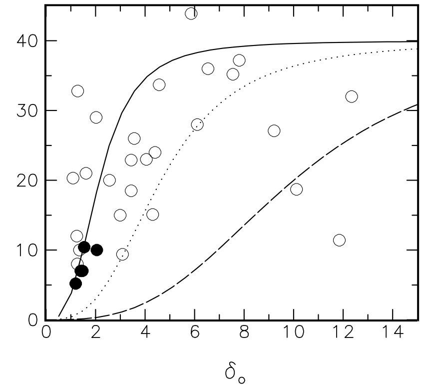

Fig. 2. The relation between optical polarization and optical Doppler factor in the case of continuous jet model ($p = 2 + \alpha$ with $\alpha = 1.0$)for RBLs (open circles) and XBLs (filled circles). The dashed curve stands for $f = 0.01$, dotted curve for $f = 0.01$ and solid curve for $f = 0.1$.

3. Conclusion

From our results mentioned above, we can conclude that (1) polarization is correlated with the beaming effect and the continu-

Table 1. BL Lac objects with known Doppler factors

(1)	(2)	(3)	(4)	(5)	(6)	(7)
0048-097	RBL		27.1	ST	10.5	
0215+015	RBL	1.715	20.0	AS		2.56
0219+428	RBL	0.444	15.0	AS		2.99
0235+164	RBL	0.940	43.9	ST	6.5	
0300+471	RBL		24.0	AS	4.8	
0317+185	XBL	0.190	5.2	J		1.20
0323+022	XBL	0.147	10.4	J		1.54
0454+844	RBL	0.112	18.5	ST	3.7	
0521-365	RBL	0.061	9.4	ST	3.3^R	
0537-441	RBL	0.896	18.7	ST	11.6	
0716+714	XBL		29.0	ST	2.1	
0735+178	RBL	0.424	36.0	I	7.3	
0754+100	RBL	0.66	26.0	I		3.56
0823+033	RBL	0.506	22.9	ST	3.7	
0851+202	RBL	0.306	37.2	ST	8.8	
0954+658	RBL	0.368	33.7	ST	5.0	
1101+384	XBL	0.030	7.0	AS		1.40
1219+285	RBL	0.102	10.0	AS		1.35
1308+326	RBL	0.997	28.0	ST	6.8	
1514-241	RBL	0.049	8.0	ST		1.26
1519-273	RBL		11.4	ST	13.7	
1538+149	RBL	0.605	29.6	ST	1.3	
1652+398	XBL	0.034	4.6	ST	1.5	
1749+096	RBL	0.322	32.0	ST	14.3	
1749+701	RBL	0.770	20.3	W	1.1	
1803+784	RBL	0.684	35.2	ST	8.5	
1807+698	RBL	0.051	12.0	AS		1.24
2007+777	RBL	0.342	15.1	ST	4.7	
2155-304	XBL	0.117	10.	J		2.05
2200+420	RBL	0.069	23.0	ST	4.4	
2254+074	RBL	0.190	21.0	AS		1.61

Col. 1: Name; Col. 2: Classification; Col. 3: Redshift; Col. 4: Optical Polarization; Col. 5: Reference for Col. 4; Col. 6: Radio Doppler Factor(Ghisellini et al. 1993); Col. 7: Optical Doppler Factor(Xie et al. 1991).

AS: Angel & Stockman 1980; I: Impey & Tapia 1990; J: Jannuzi et al. 1994; R: Romero et al. 1995; ST: Stickel et al. 1993; W: Wills et al. 1992

ous jet model may be more reasonable than the spherical model; (2) the large difference in the polarizations between RBLs and XBLs is from the difference in the beaming effect. (3) This scenario can explain the differences in luminosities, multiwavelength correlations, different spectral indices, and the difference in the polarizations between RBLs and XBLs, but the viewing angle effect alone cannot explain the spectral energy distribution between RBLs and XBLs (Sambruna et al. 1996).

Acknowledgements. This work is supported by an RGC grant of Hong Kong Government, a CRCG grant of the University of Hong Kong, and the National Natural Scientific Foundation of China. The authors thank the anonymous referee for his constructive comments and T.C. Boyce for the critical reading.

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