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Superluminal Motion and Polarization in Blazars *

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Abstract A relativistic beaming model has been successfully used to explain the observed properties of active galactic nuclei (AGNs). In this model there are two emission components, a boosted one and an unbeamed one, shown up in the radio band as the core and lobe components. The luminosity ratio of the core to the lobe is defined as the core-dominance parameter ($R = \frac{L_{\rm Core}}{L_{\rm Lobe}}$). The de-beamed radio luminosity ($L_{\rm jet}^{\rm db}$) in the jet is assumed to be proportional to the unbeamed luminosity ($L_{\rm ub}$) in the co-moving frame, i.e., $f = \frac{L_{\rm jet}^{\rm db}}{L_{\rm ub}}$, and f is determined in our previous paper. We further discuss the relationship between BL Lacertae objects (BLs) and flat spectrum radio quasars (FSRQs), which are subclasses of blazars with different degrees of polarization, using the calculated values of the ratio f for a sample of superluminal blazars. We found 1) that the BLs show smaller averaged Doppler factors and Lorentz factors, larger viewing angles and higher core-dominance parameters than do the FSRQs, and 2) that in the polarization-core dominance parameter plot ($P - \log R$) the BLs and FSRQs occupy a scattered region, but in a revised plot ($\log \frac{P}{c(m)} - \log R$), they gather around two different lines, suggesting that they have some different intrinsic properties.

Key words: active galactic nuclei — superluminal motion — jets — relativistic beaming model

1 INTRODUCTION

Many active galactic nuclei (AGNs) contain compact radio sources with components that appear to move apart in successive high-resolution VLBI images. When the apparent transverse velocity ($\beta_{\rm app} = v/c$) exceeds the speed of light, the motion and the object are called superluminal. Superluminal motion has now been observed in dozens of sources (Pearson &

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Zensus 1987; Vermeulen & Cohen 1994). A subclass of AGNs are blazars, which includes BL Lacertae objects (BLs) and flat spectrum radio quasars (FSRQs).

A popular kinematic explanation for superluminal motion is that the nuclear region contains a narrow, nearly straight, expanding jet of plasma in relativistic motion, and when the jet is pointing close to the line of sight, contraction of the apparent timescale can result in superluminal motion. The main observational properties of superluminal objects are now well established (Zensus & Pearson 1988; Ghisellini et al. 1993; Vermeulen & Cohen 1994). In our previous papers, we showed that there is an association between their radio and optical enhancements and that the acceleration model is reasonable (Fan et al. 1996), and we obtained some statistical results for a sample of such sources (Fan 1998). Very recently, combining the superluminal velocity, the Doppler factor and the core-dominance parameter (the core to lobe luminosity), we determined the ratios f (the de-beamed to the unbeamed radio luminosity) for a sample of sources (Fan 2003).

High, variable polarization is a typical characteristic of blazars, they inform the magnetic field and relativistic beaming effect. Many authors have made observations and theoretical analyses on this topic (Angel & Stockman 1980; Impey & Tapia 1990; Wills et al. 1992; Fan et al. 1997; Efimov et al. 2002). The researches show that the two subclasses have different degrees of polarization with the BLs showing higher polarizations than do the FSRQs. Work on polarization is important for our understanding of the relation between the two subclasses. In the present paper, we will investigate this relation further. In Section 2 we describe our sample and the results obtained; in Section 3 we carry out a discussion, ending with a brief concluding statement.

2 DATA AND RESULT

2.1 Data

In our previous paper, to determine the ratio f, we chose sources with known superluminal motion velocity, Doppler factor and core-dominance parameter (Fan 2003). Different methods (Xie et al. 1991; Ghisellini et al. 1993; Jiang et al. 1998; Fan et al. 1999; Cheng et al. 1999; Lahteenmaki & Valtaoja 1999) had been used to determine the Doppler factors. Since the Doppler factor determined from radio variability has advantages over the others, we used the data given by Lahteenmaki & Valtaoja (1999). From our previous paper (Fan & Lin 2003; Fan 2003), we chose 35 sources (25 FSRQs and 10 BLs) with known polarizations. These are listed in Table 1.

2.2 Results

From the relativistic beaming model, one can obtain the viewing angle θ and the Lorentz factor Γ, from the Doppler factor, δ and the apparent (superluminal) velocity $\beta_{\rm app}$, namely

$$\Gamma = \frac{\beta_{\rm app}^2 + \delta^2 + 1}{2\delta}, \tag{1}$$

$$\tan\theta = \frac{2\beta_{\rm app}}{\beta_{\rm app}^2 + \delta^2 - 1}. \tag{2}$$

When we considered the BLs and FSRQs separately, we obtained the following results (Table 2).

Table 1 Data for a Sample of Superluminal Sources

Name (1)	ID (2)	δ (3)	$\beta_{\rm app}$ (4)	$\log R$ (5)	Ref (6)	$P_{\rm opt}(\%)$ (7)	Ref (8)	$\log f$ (9)
0016+731	FQ	18.39	8.35	0.50	G	1.1	I90	–3.29
0106+013	FQ	8.62	8.20	0.90	C	7.1	F97	–1.91
0212+735	FQ	4.16	3.88	2.64	C	7.8	F97	0.78
0219+428	BL	1.99	14.89	0.77	FW	18.0	F01	–0.13
0234+285	FQ	7.29	9.29	2.00	C	11.3	I90	–0.59
0235+164	BL	16.32	7.10	1.69	C	43.9	F97	–1.95
0333+321	FQ	6.48	4.77	1.50	BM	1.0	F98	–0.93
0336–01	FQ	19.01	8.9	1.50	C	19.4	F97	–2.34
0420–014	FQ	11.72	4.80	2.40	C	20.0	F97	–0.81
0440–00	FQ	11.46	6.10	1.30	C	12.6	I90	–1.88
0458–020	FQ	17.80	4.09	0.70	C	17.3	I90	–3.05
0528+134	FQ	14.22	5.15	1.60	G	0.3	I90	–1.86
0605-085	FQ	4.53	4.4	1.46	C	10.0	I90	–0.51
0735+178	BL	3.17	5.84	3.92	FW	36.0	F01	2.42
0836+710	FQ	10.67	7.69	1.54	C	1.0	I91	–1.54
0851+202	BL	18.03	2.95	2.89	C	37.2	FL	–0.88
0923+392	FQ	2.25	3.97	1.20	C	0.8	F98	0.14
0954+658	BL	6.62	5.7	2.04	C	33.7	I91	–0.42
1055+018	FQ	7.78	2.30	1.33	C	6.0	F99	–1.34
1156+295	FQ	9.42	5.20	0.83	FB	28.0	F99	–2.09
1219+285	BL	1.56	2.00	3.45	FA	20.0	F01	2.87
1226+023	FQ	5.71	6.10	0.80	C	2.5	I90	–1.47
1253–055	FQ	16.77	4.87	1.10	C	44.3	F97	–2.57
1308+326	BL	11.38	10.80	1.56	C	28.0	FL	–1.61
1510–089	FQ	13.18	3.77	1.50	C	7.8	I90	–1.86
1606+106	FQ	9.32	2.90	0.83	FU	2.1	I90	–2.08
1611+343	FQ	5.04	11.40	1.40	BM	1.7	I90	–0.71
1633+382	FQ	8.83	4.80	1.90	C	2.6	I91	–0.94
1641+399	FQ	7.45	6.32	1.50	C	35.0	F99	–1.12
1803+784	BL	6.45	1.80	2.69	C	35.2	FL	0.26
1928+738	FQ	3.71	4.97	0.70	G	3.3	F98	–1.01
2007+777	BL	5.13	2.33	1.90	G	15.1	F98	–0.23
2200+420	BL	3.91	3.28	2.41	FA	23.0	FL	0.63
2230+114	FQ	14.23	8.86	1.40	C	10.9	I90	–2.06
2251+158	FQ	21.84	7.19	1.20	C	16.0	F99	–2.82

Col. 1, Source name; Col. 2, Identification (FQ for FSRQ); Col. 3, Doppler factor (δ), (from Lahteenmaki & Valtaoja (1999)); Col. 4, superluminal velocity ($\beta_{\rm app}$), (from Lahteenmaki & Valtaoja (1999)); Col. 5, Core-dominance Parameter(R); Col. 6, reference for the core-dominance; Col. 7, maximum optical polarization ($P_{opt}\%$); Col. 8, reference for optical polarization; Col. 9, $\log f$.

The references listed in the table are BM: Browne & Murphy (1987); C: Cao & Jiang (2001); FA: Antonucci & Ulvestad (1985); FB: Wills & Browne (1986); FU: Ulvestad et al. (1981); FW: Wills et al. (1992); F01: Fan et al. (2001); F98: Fan et al. (1998); F97: Fan (1997); FL: Fan & Lin (1999); G: Ghisellini et al. (1993); I90: Impey & Tapia (1990); I91: Impey et al. (1991).

Table 2 Averaged Values for Two Classes of Superluminal Sources

	Γ	θ	δ	$\log R$	$\log R_T$	$\log f$
FSRQs	7.44±0.52	6.15°±0.95	10.19±0.92	1.27±0.11	−3.83±0.24	−1.59±0.19
BLs	6.16±1.07	10.43°±3.23	7.45±1.85	2.33±0.30	−2.10±0.73	0.11±0.49

Polarization is associated with the core-dominance parameter (see Wills et al. 1992 and reference therein), with higher polarization corresponding to larger $\log R$. From our previous papers (Fan et al. 1997; Fan et al. 2001), we have

$$\frac{10^{-0.4m_1^{\rm ob}}P_1^{\rm ob}}{\delta_1^{3+\alpha}} = \frac{10^{-0.4m_2^{\rm ob}}P_2^{\rm ob}}{\delta_2^{3+\alpha}} = k\,,$$

which suggests a relation between polarization and the core-dominance parameter at a given magnitude:

$$P^{\rm ob} = k\ \delta^{3+\alpha}\ 10^{0.4m^{\rm ob}} = \left(\frac{k}{f}\right)10^{0.4m^{\rm ob}}(f\delta^{3+\alpha}) = c(m)R\ \propto R\,, \qquad (3)$$

where $c(m) = (\frac{k}{f})10^{0.4m^{\rm ob}}$ is a parameter that depends on magnitude $m^{\rm ob}$, on the constant k and on the ratio f. Relation (1) shows that a high polarization is associated with a large core-dominance parameter. In the present paper, polarization is again found to be associated with the core-dominance parameter, i.e., the higher the polarization the higher the core-dominance is, as shown in Fig. 1.

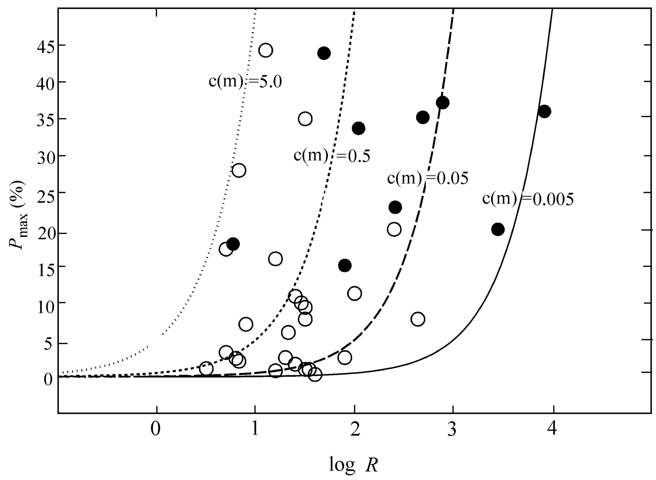

Fig. 1 Plot of polarization ($P_{\rm opt}(\%)$) vs. core-dominance parameter ($\log R$) for the whole sample (filled circles for BLs, open ones for FSRQs). The curve stands for $P = c(m)R$ with $c(m) = 0.005$, 0.05, 0.5 and 5, respectively.

3 DISCUSSION

Blazars (BLs and FSRQs) are an extreme subclass of AGNs, they show rapid and high amplitude variation, superluminal motion, high and variable polarization, and high energy emissions. BLs and FSRQs show almost the same observational properties except that they have different emission line properties with the BLs having very weak or no emission lines while the FSRQs having strong emission features. The BLs have higher optical polarization than the FSRQs, on average. Sometimes, the FSRQs also show very weak emission line features such as the case of 3C 279, claimed by Scarpe & Falomo (1997).

The core dominance parameter R (the ratio of core to extended radio fluxes) is an important parameter and has been proposed as an indicator of the orientation of the emission (Orr & Brown 1982), and of relativistic beaming (Ghisellini et al. 1993; Hough & Readhead 1987). It is clear that R is useful in determining the ratio f.

As shown in Fig. 1, the polarization is found associated with the the core-dominance parameter and the observed maximum polarization increases with the latter. The points are scattered in an area bounded by $c(m) = 0.005$ and $c(m) = 5$. The range in $c(m)$ is 3 dex for the whole sample. These scattered points refer to different values of c(m) for different sources. Since $c(m) = \frac{k}{f}10^{0.4m}$, the scatters in both the optical magnitude ($m^{\rm ob}$) and $c(m)$ will result in a scatter in f for $f = \frac{k}{c(m)}10^{0.4m}$. Since the scatter in the optical band is about 5 stellar magnitudes or 2 dex (Fan et al. 2001) and that in $c(m)$ is 3 dex, we obtain the difference in f to be about 5 dex. It is interesting that this range in f is quite consistent with that obtained in our calculation, which shows that the values of f are mainly in the region between $\log f = -3.29$ for the FSRQ 0016+731 to 2.87 for the BL 1219+285 (see Table 1), corresponding a range of 6.1 dex in f. It should be pointed out that Eq. (3) implies that polarization is correlated with core-dominance, but because the correlation coefficient $c(m)$ depends on both the ratio f and the magnitude $m^{\rm ob}$, which are different from one source to another, the correlation is diluted, hence the scattering of the points in Fig. 1. For a group of sources with similar f-ratios and magnitudes ($m^{\rm ob}$), one may expect a tighter correlation. Unfortunately, this is not the case considered in this paper. However, for sources with different f values, we can consider a revised correlation between polarization and core-dominance parameter, which we now describe.

Equation (3) suggests that there is a linear correlation between $\frac{P^{\rm ob}}{c(m)}$ and R. To investigate this correlation, one should take the magnitude for each source, which is available from the Veron-Cetty & Veron (1998) catalog. Based on the optical magnitudes and the known ratios f (Fan 2003), we can make a plot of $\frac{P^{\rm ob}}{c(m)}$ against R for the FSRQS and BLs; see Fig. 2. The plot suggests a statistical linear correlation between $\frac{P^{\rm ob}}{c(m)}$ and R, namely

$$\log \frac{P^{\rm ob}}{c(m)} = (1.89 \pm 0.08) \log R - 10.2 \pm 0.21 \,.$$

This is different from the expected result,

$$\log \frac{P^{\rm ob}}{c(m)} = \log R + {\rm const}\,.$$

However, when we consider the BLs and FSRQs separately, we obtain

$$\log \frac{P^{\rm ob}}{c(m)} = 1.12 \log R - 7.37$$

for the BLs, and

$$\log \frac{P^{\rm ob}}{c(m)} = 0.92 \log R - 9.14$$

for he FSRQs, with correlation coefficient and chance probability $r = 0.713$ and $p = 3.2\%$ for the BLs and $r = 0.367$ and $p = 3.4\%$ for the FSRQs. The slopes are consistent with the expectations. It implies that the dependence of polarization on the relativistic beaming model is the same for BLs and FSRQs. The difference in the constant term probably means 1) that the magnetic field is not the same for the two subclasses, since the polarization in blazars depends on the boosting effect and the magnetic field (Fan et al. 1997); and 2) that the observed polarization is not always the maximum value for the object considered;—another factor that dilutes the expected correlation. Therefore, further polarization observations and researches on this correlation will be useful.

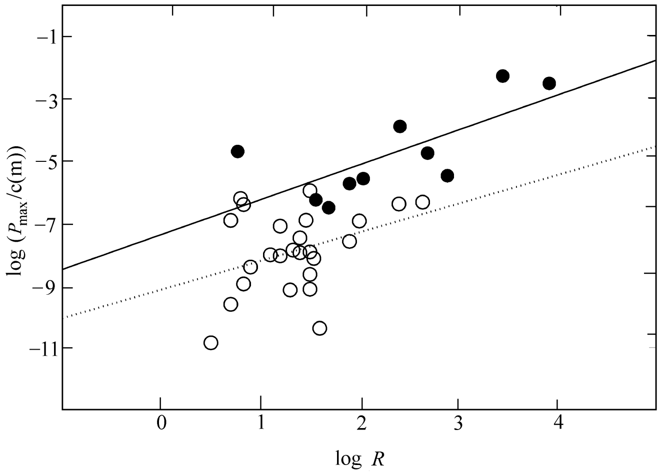

Fig. 2 Plot of polarization ($\log \frac{P^{\rm ob}}{c(m)}$) vs. core-dominance parameter ($\log R$) for the whole sample (filled circles represent BLs, open ones for FSRQs). The solid line stands for the best fitting result for BLs, the dotted line for FSRQs (see text).

BL Lac objects and FSRQs (or optical violently variable quasars-OVVs) show some very similar observational properties, but their differences in the emission lines are also obvious. Some authors proposed that both the two subclasses are in different evolutional stages as emission line objects evolve into non-emission line objects. However, we notice that the ratio f of the de-beamed to unbeamed luminosity plays an very important role in explaining the difference in the emission lines (Fan 2003). Fan (2002) compared the polarization-Doppler factor relations for BLs and for FSRQs (in that paper we used the name OVVs, while in the present paper we use FSRQs), and found that the polarization/core-dominance points of the two subclasses can be fitted by different f and η, η being the ratio of polarized to unpolarized emission in the de-beamed jet emission. Since the intrinsic polarization in the jet frame is defined as $P^{\rm in} = \frac{f}{1+f}\frac{\eta}{1+\eta}$ (see Fan et al. 1997), the results of fitting (Fan 2002) suggested that the intrinsic polarization is lower in the FSRQs than in the BLs. That is why the Doppler factor is higher in the FSRQs than in the BLs, while the polarization is lower.

Adopting the two-component model (see Urry & Shafer 1984), if f is the same in the different wavebands for a given source, then we have

$$L^{\rm ob} = L_{\rm unb} + L_j^{\rm ob} = L_{\rm unb} + f\delta^p L_{\rm unb}\,. \quad (4)$$

Let the unbeamed emissions be proportional to line emissions; we can then check the difference in emission line between the BLs and FSRQs. Observations show that there is no emission line or only very weak emission lines in BLs, while there are strong emission lines in FSRQS. In the present paper, the Doppler factors in BLs and FSRQs are comparable, but the average value of f of the BLs is 1.68 dex greater than that of the FSRQs. So, for the large f in BLs, the second term is much greater than the first in the right side of Equation (4), namely, $L^{\rm ob} \approx f\delta^p L_{\rm unb} = L_j^{\rm ob}$, and only emissions from the jet are observed. For the FSRQs, because f is so small that the two terms in the right side of Eq. (4) are comparable. So the emissions from both the jet and unbeamed components are observed, that is why we can observe emission lines in FSRQs. In this sense, we can explain why there are strong emission lines and lower polarization in FSRQs than in BLs.

We have compiled a sample of superluminal blazars with known Doppler factors, optical polarizations and core-dominance parameters and used the known ratios, f, optical polarization, and core-dominance parameter, to compare BLs and FSRQs. We found the two subclasses to have different values of the parameters. However, they obey a revised polarization and core-dominance parameter relation suggesting that their polarization is caused by beaming effect. We have also used the difference in f to explain their difference in emission lines.

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