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Photometric and Polarimetric Behavior of the High-Redshifted BL Lacertae Object PKS 0215+015 in 1984–86*

Sen KIKUCHI

National Astronomical Observatory, Mitaka, Tokyo 181

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Abstract

PKS 0215+015, the most distant source among the known BL Lac objects, underwent an outburst in 1984–85 and also a small scaled one in 1986. During about 120 days in 1984–85 and about a month in 1986, we made multichannel photometry and polarimetry of this object in the optical region. Combining the observed luminosities and the time scales of the 50% flux variation, we find cases that a relation limiting the validity of the isotropic emitting model is broken. Also, the large swings of polarization angles amounting to about 50° and −100° during 36 and 22 days, respectively, after the correction for the redshift, were associated with rapid variations of the flux. These results strongly suggest the presence of relativitstic motion in the source and it is the first case that the relativistic beaming model has been supported on both photometric and polarimetric bases at the same time. The rapid variations in flux and polarization are explained by a relativistically moving cloud in an accelerated state or by the shock-illuminated radiation in the nonaxially symmetric magnetic field depending on whether or not the amount of variations in polarization angles exceeds 180°. Further problems associated with the interpretation by the relativistic beaming model are also discussed.

Key words: Active galactic nuclei; BL Lac objects; Polarization; Relativistic beaming; Variability.

1. Introduction

As one of the models to explain the observed phenomena in active galactic nuclei, the relativistic beaming model has been developed extensively (Rees 1966; Blandford and Rees 1978; Blandford and Königl 1979; Scheuer and Readhead 1979; Marscher 1980; Königl 1981; Blandford 1984; Ghisellini et al. 1985). The beaming model explained successfully the superluminal motion observed in several compact radio

* Based on observations made at the Dodaira Station (DS) and the Okayama Astrophysical Observatory (OAO). DS and OAO are branches of the National Astronomical Observatory, an inter-university research institute operated by the Ministry of Education, Science, and Culture.

sources [Cohen and Unwin (1984) and references therein]. Also, spectral features at overall frequencies suggest the presence of the effect due to the beaming (e.g., Worrall et al. 1984) and the importance of the model has been increased by the finding of jets associated with active galactic nuclei.

As the characteristics due to a relativistically moving source, rapid changes of flux and polarization properties are also expected (Blandford and Königl 1979; Björnsson 1982). Blandford and Königl (1979) explained the large swing of polarization angle observed in AO 0235+164 by Ledden and Aller (1978) in the radio region using the relativistic beaming model. Also, Königl and Choudhuri (1985a, b) interpreted the swing of the polarization angle over 180° observed in several active radio sources (Altschuler 1980; Aller et al. 1981) in terms of the relativistic beaming. Although many efforts have been made, up to now, few results have been obtained to invoke bulk motion in the optical region. The number of observations in this field is not yet sufficient, and the studies on the magnetic field and the source dynamics based on photometry and polarimetry are clearly needed.

PKS 0215+015 was optically identified as an 18.5-mag object of stellar appearance and the variability was detected by Bolton and Wall (1969, 1971). Spectroscopic observations by Gaskell (1982) and Blades et al. (1982a, 1985) showed a power-law continuum and no emission-line features exhibiting the characteristics of BL Lac objects. Seven absorption systems of $z=1.254$, 1.345, 1.491, 1.549, 1.649. 1.686, and 1.719 were distinctly observed, and at high resolution some of these absorption systems showed complex structures (Gaskell 1982; Blades et al. 1982a, 1985; Pettini et al. 1983). The observations with the IUE also show similar spectral characteristics (Blades et al. 1982b, 1985). Blades et al. (1985) suggested an emission feature at $z=1.715$ and Foltz and Chaffee (1987) confirmed the existence of an emission system of $z=1.715$ by spectrophotometry in a faint state. This value of the redshift of $z=1.715$ in PKS 0215+015 indicates that the source is one of the most distant sources among the known blazars, i.e., BL Lac objects and highly polarized quasars. According to Gaskell (1982) and Blades et al. (1982a, 1985), the object was in a bright state since 1978 with a fade to $B>18.5$ mag in mid-1983, and in 1984 August brightened as $V=14.0$ mag (Brindle et al. 1986). The strong and variable polarization was also observed by J. S. Miller and G. D. Schmidt [quoted by Gaskell (1982)], Bailey et al. (1983), and Brindle et al. (1986). Since 1984 October, we have tried to make photometry and polarimetry of the source to investigate the rapid variability, although in faint phases observations were impossible.

The study of the variability of high-redshifted objects has particular importance, since the time scale of the variation in the frame associated with the source is the observed one multiplied by a factor of $1/(1+z)$, if we assume isotropic emission. PKS 0215+015 is one of the most adequate objects for the study of this kind, in other words, for the study of the minimum time scale of the variation in active galactic nuclei. The study will greatly contribute to the study of the validity of the existing models of active galactic nuclei. It should be also mentioned that, in the observations of distant sources like PKS 0215+015 from a single observatory, we are free from systematic errors inevitably associated with multisite observations.

2. Observations

Photometric and polarimetric observations were made simultaneously with the multichannel polarimeter (Kikuchi 1988) attached to the 91-cm telescope of the Dodaira Station and to the 188-cm telescope of the Okayama Astrophysical Observatory of the National Astronomical Observatory. At Dodaira, we observed the source typically with an integration time of 2 min including the measurement of the sky brightness. Also, we observed every 15 min a nearby comparison star which was established on the basis of the photometric standard stars in the equatorial region (Moffett and Barnes 1979). The variability of the comparison star itself was checked by the observation of a nearby star, HD 14214, which had been studied already photometrically (Roman 1955; Cousins 1962), and no variation of greater than 0.02 mag was found. At Okayama, we made similar observations during January 14–17, 1985. The integration time for a single observation was about 80 s, and about every 10 min we calibrated with the comparison star. However, unfortunately the weather was not so good for photometry to detect a very rapid variation.

For the polarimetric observations, the situation was the same. Always we made polarimetry simultaneously with photometry, since the optical components of the multichannel polarimeter were sufficiently transparent in the wavelength region of 0.31–1.1 μm, and an achromatic half-wave plate of Pancharatnam's (1955) type followed by a Wollaston prism was used. The signals were modulated with a frequency of 10 Hz in 1984–85 and 20 Hz in 1986. Corrections for the instrumental polarization were made by the observations of unpolarized stars listed by Serkowski (1974) and the amount of polarization of the instrumental origin was always less than 0.3% in the *V* region. The origin of polarization angles is determined by the assumption that the polarization angle for the highly polarized star 9 Gem to be 170°. Also, in the course of the observing work, we occasionally checked a depolarizing effect in the instrument and the constancy of the origin of polarization angles by inserting a quartz polarizer ahead of the diaphragm. We have found neither drastic nor unexpected change of the polarization of the instrumental origin.

3. Observational Results

3.1. Variations of the Optical Flux and Colors in 1984–85.

Photometric and polarimetric results during the observing period are given in table 1 and also displayed in figures 1a–c. The accuracy of the photometric and polarimetric data in the first half of the observing period in 1984–1985 is superior, mainly because of good weather conditions. From an inspection of figure 1a, we find that the variation of the optical flux of large amplitude has occurred. On November 5, 1984 the visual magnitude of 14.45 was observed and then the optical flux decreased rather monotonically till the end of December. From January 14 to February 20, 1985 the source has once more brightened and reached a level of 15.0 mag in the *V* region. As seen in figure 1a, besides the long-term trend mentioned above, the fluctuations of the optical flux on smaller time scales are clearly present, for example, in December 1984. Before the start of our observations, Brindle et al. (1986) and Webb

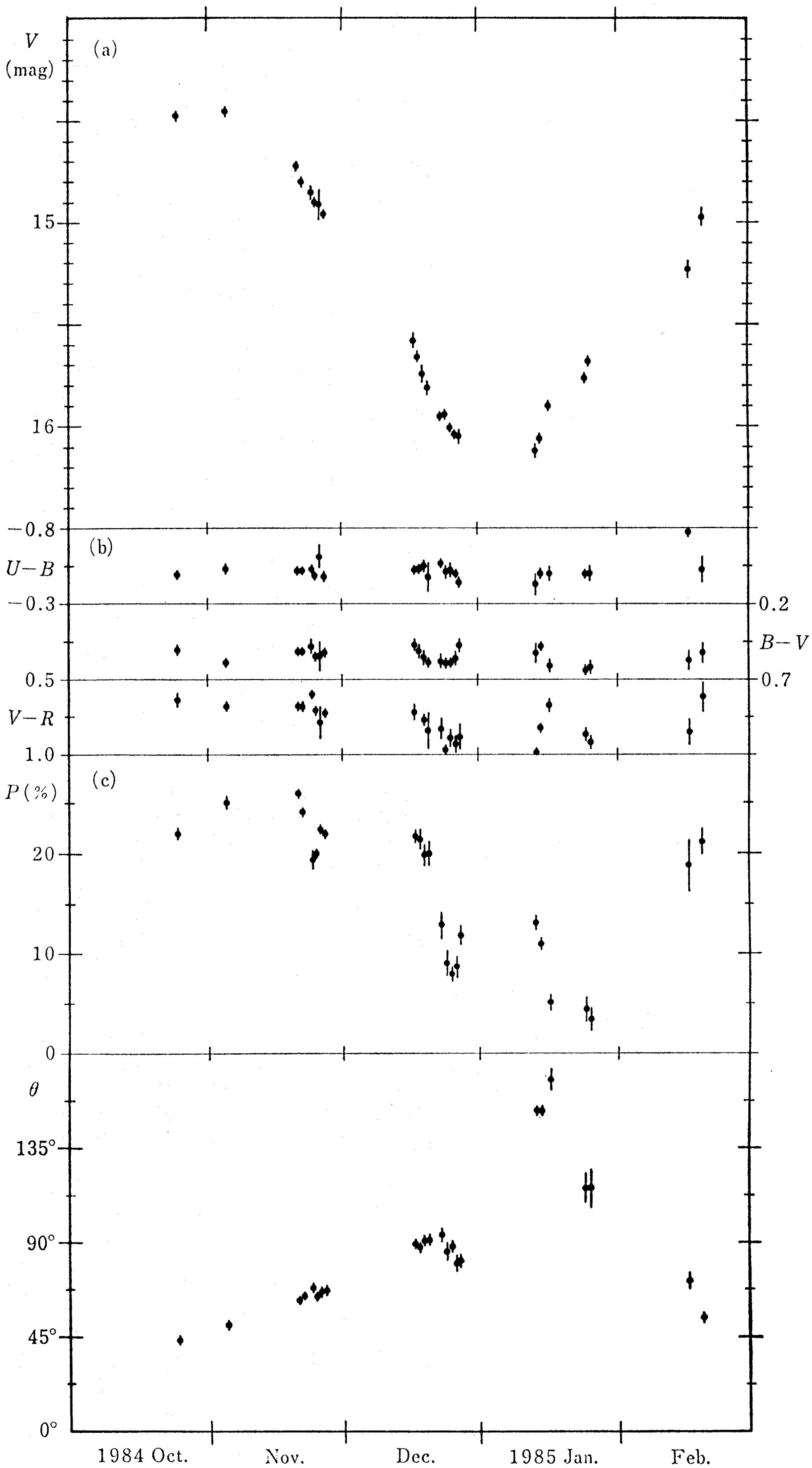


Fig. 1. The variations of (a) *V* magnitude, (b) color indices, and (c) polarization properties.

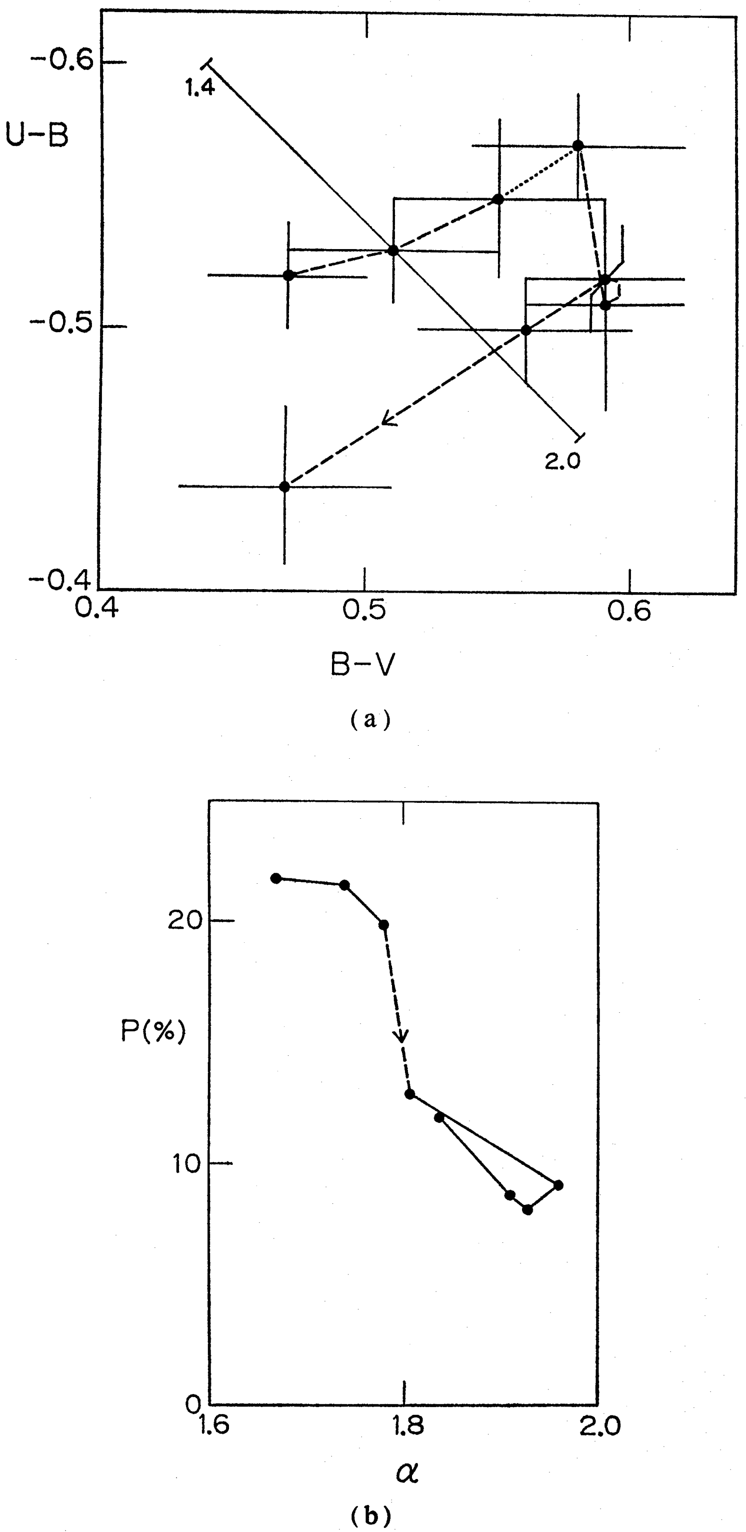


Fig. 2. The behavior during December 20–27, 1984. (a) The behavior on the two-color diagram. The line for the power-law spectrum after Matthews and Sandage (1963) is also shown with the values of spectral indices. (b) The relation between the polarization and spectral index. The data obtained with an interval of one day are combined by the dashed line and the others by the dotted line in (a), while the solid line and the dashed line are used in (b).

Table 1. Photometry and Polarimetry of PKS 0215+015.

Date (UT)	V		$U-B$		$B-V$		$V-R$		P (%)		P.A. (deg)	
84–10–25.67......	$14^{\rm m}.48\pm$	$^{\rm m}.02$	$-^{\rm m}.49\pm$	$^{\rm m}.01$	$^{\rm m}.50\pm$	$^{\rm m}.03$	$^{\rm m}.64\pm$	$^{\rm m}.04$	22.0±	0.4	43.5±	0.6
84–11–05.64......	14.45	.01	−.53	.02	.59	.02	.68	.02	25.1	0.5	50.8	0.6
21.61......	14.72	.01	−.52	.01	.51	.01	.68	.02	26.0	0.3	62.8	0.3
22.55......	14.80	.01	−.52	.01	.51	.01	.68	.02	24.1	0.2	64.6	0.3
24.66......	14.85	.03	−.53	.01	.48	.05	.60	.15	19.4	0.7	68.4	1.1
25.52......	14.90	.02	−.49	.01	.54	.02	.71	.02	20.0	0.3	64.3	0.5
26.43......	14.91	.07	−.61	.08	.54	.09	.79	.11	22.4	0.3	66.5	0.4
27.53......	14.96	.01	−.48	.01	.52	.01	.73	.01	21.9	0.2	67.0	0.3
84–12–17.45......	15.58	.03	−.52	.02	.47	.03	.72	.05	21.7	0.5	89.2	0.7
18.44......	15.66	.02	−.53	.02	.51	.04	1.15	.05	21.4	0.9	87.5	1.2
19.45......	15.74	.04	−.55	.03	.55	.04	.77	.02	19.8	1.0	91.0	1.4
20.53......	15.81	.03	−.48	.09	.59	.15	.84	.12	20.0	1.2	91.1	1.8
23.42......	15.95	.01	−.57	.02	.58	.04	.83	.07	12.9	1.3	93.8	2.9
24.49......	15.94	.02	−.51	.04	.59	.03	.97	.02	9.1	1.2	85.7	3.9
25.48......	16.01	.02	−.52	.02	.59	.03	.89	.05	8.1	0.7	88.1	2.3
26.56......	16.04	.01	−.50	.02	.56	.04	.93	.05	8.7	1.0	80.1	3.3
27.50......	16.05	.03	−.44	.03	.47	.04	.89	.09	11.9	0.9	81.1	2.2
85–01–14.45......	16.12	.03	−.43	.07	.52	.05	.99	.06	13.1	0.7	153.0	1.5
15.43......	16.06	.02	−.50	.03	.48	.02	.82	.02	11.0	0.5	152.7	1.3
17.43......	15.90	.02	−.50	.05	.62	.04	.92	.03	5.1	0.8	167.7	4.8
25.45......	15.76	.02	−.50	.02	.64	.03	.87	.04	4.4	1.0	116.0	6.7
26.44......	15.68	.02	−.50	.05	.62	.04	.92	.03	3.4	1.1	115.9	8.9
85–02–17.42......	15.23	.04	−.77	.07	.57	.06	.85	.08	18.8	2.5	71.8	3.8
20.44......	14.97	.03	−.53	.08	.52	.06	.61	.09	21.1	1.1	53.7	1.5
86–12–05.51......	16.66	.04	−.67	.05	.65	.03	1.27	.05	17.4	1.3	66.8	2.1
06.51......	16.72	.03	−.77	.11	.74	.04	1.38	.05	14.2	1.8	86.2	3.7
26.45......	16.79	.05	−.78	.12	.69	.06	1.38	.08	4.8	2.5	40	15
30.40......	16.64±	.04	−.59±	.05	.66±	.07	1.29±	.07	11.1±	2.5	114.9±	6.5

et al. (1988) observed the source to be bright as $V\sim 14.0$ on August 17–21, 1984 and $B\sim 14.0$ on October 20, respectively. Thus, our observations were carried out in the course of fading and recovery of the source. Although it was very interesting to pursue further photometric behavior, it was impossible to continue the obeservation because of the end of the observing season.

The variation of the colors with time are also shown in figure 1b. The averaged value of the spectral indices during the observing period is about 1.85 ($F_\nu \propto \nu^{-\alpha}$), with the absolute calibration by Matthews and Sandage (1963) for the UBV region, and for R after Johnson (1966). The presently obtained value is similar to those of 1.5–2.1 obtained in the previous studies (Gaskell 1982; Blades et al. 1982a), if we consider rather large errors in the previous measurements. It is also consistent with the values generally found in blazars (Angel and Stockman 1980; Moore and Stockman 1981). However, in the brighter phase, Brindle et al. (1986) observed a much flatter spectrum, i.e., the spectral index of α=0.9–1.1, in the optical and near-infrared regions.

Next, we will examine the short-term behavior. As a departure from the gross trend of the light variation, we notice a rapid decrease of the flux during December 20–27. In the first half of this period, the feature of the flux variation was slightly different from that of the long-term in October–November. The rate of the flux decrease became smaller in the second half of this period, and it may be interpreted to be due to the fact that another faint component was growing. At the same time, the colors $B-V$ and $V-R$ became redder, while $U-B$ became more negative. The trajectory on the $(U-B)$-$(B-V)$ diagram was almost perpendicular to the line which represents the power-law spectrum as shown in figure 2a. A similar behavior on the two-color diagram was also found in OJ 287 (Kikuchi et al. 1973). Therefore, this is considered as one of common phenomena associated with the rapid change of the flux in the optical region.

3.2. *Variations of Polarization Properties in 1984–85*

Polarimetric results in 1984–85 are given in table 1 and figure 1c. The polarization varied greatly with the light variation. The most impressive is that the polarization angle has varied almost linearly with time during October 25–December 23, 1984 and January 14–February 20, 1985. The swings of the polarization angle amounted to about 50° and −100° for the former and latter periods, respectively. Another systematic and more rapid change of the polarization angle was found during December 23–27. Also, during December 27–January 14, the polarization angle varied at least by 70°. It should be noted that the polarization angle could have possibly varied by −110°, if an ambiguity of 180° in the determination of the polarization angle is taken into account. If the amount of the change of the polarization angle was −110° instead of 70° at this epoch, the polarization angle is considered to have varied by about 220° during the period of December 23–February 20.

The polarization degree did not show simple behavior with time on the contrary to the cases for the optical flux and the polarization angles. Till December 20, the polarization was larger than 20% with fluctuations, and then a drastic weakening followed by a rapid recovery was observed. During January 14–February 20, with the large swing of the polarization angle, the polarization strength varied from 10–13% to 3–5% in late January, and once more increased to a level of 20%. It should be noted especially for the December data that systematic variations of the polarization degrees and of the spectral shape occurred as shown in figure 2b.

On the other hand, the behavior of the polarization angle was obeying the long-term trend till December 20. During the following several days, December 23–27, however, a distinct variation of the polarization was found. The polarization angle varied abruptly in the direction opposite to the long-term one since October 25, and the polarization degree showed a sharp minimum. A similar minimum of the polarization strength but much weaker was also found around November 24, although the behavior of the polarization angle was not so clear as during December 23–27.

The wavelength dependence of polarization was not generally observed except for a few cases. On November 27 and December 18, and probably also on December 19 the shorter the wavelength became, the stronger the polarization became as displayed in figure 3. However, there was no case in which the polarization angle depended on wavelength. It seems that no special event on the photometric behavior is associated with the wavelength dependence of polarization.

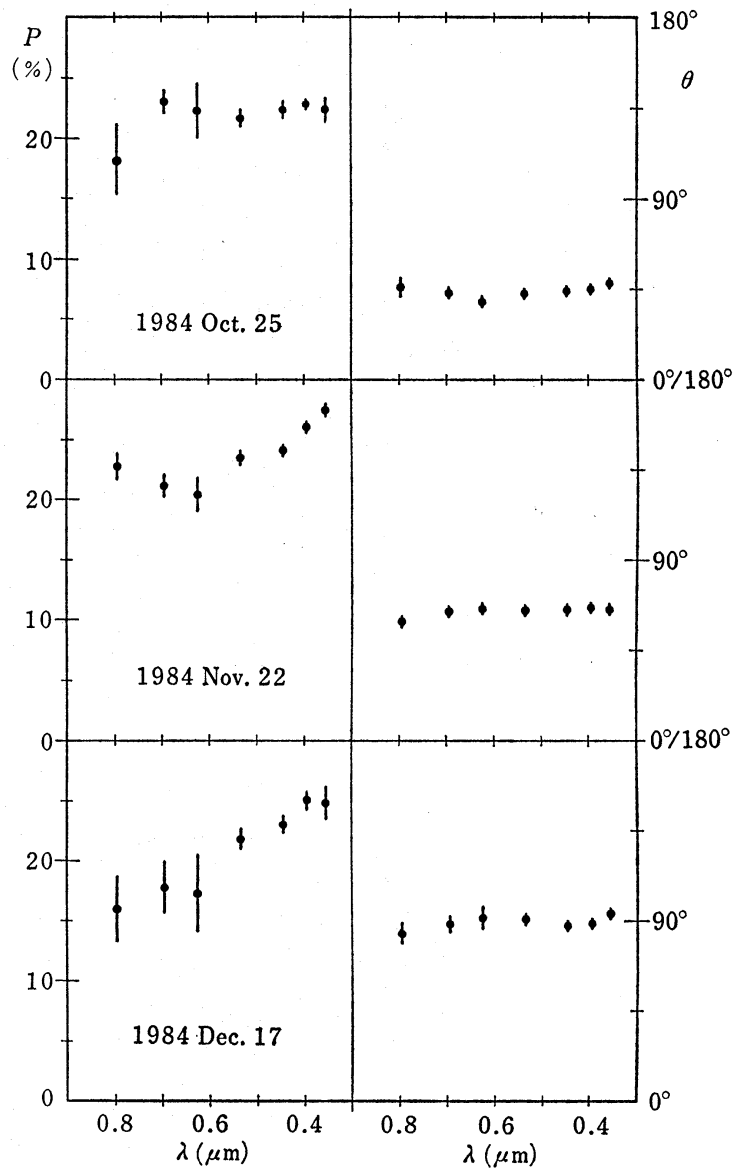


Fig. 3. Examples of the wavelength dependence of the polarization (November 22, December 17, 1984). A case without wavelength dependence is also shown as an example (October 25, 1984).

3.3. Behavior in 1986

After the end of the observing season in 1984–85, we have occasionally tried to watch the source on the TV monitoring screen of the 91-cm telescope at Dodaira. The limiting magnitude in the V region by the TV monitoring was about 16.5 mag before summer, 1986 and 16.8–17.0 mag since then because of the introduction of an integration system for the video signals. On December 5, 1986 we found that the source once again brightened to $V\sim 16.7$ mag. The results in 1986 are included in table 1. Although we intended to make photometry and polarimetry, the brightness in 1986 was not sufficient to make extensive observations.

About a month before the brightening in December, 1986, on November 1, 1986

Foltz and Chaffee (1987) found that the source was very faint as $V\sim 19.0$ mag. Therefore, the brightness increase during 34 d amounted to 2.3 mag in the V region. The color $B-V$ in the faint state is estimated to be 0.55 ± 0.05 on the basis of the photometric data in the AB magnitude scale (Oke 1974) presented by Foltz and Chaffee (1987). This value for $B-V$ yields the spectral index of about 1.87, which is quite similar to the mean value obtained in 1984–85. However, our results in 1986 December show redder color, although the observations in December, 1986 were not so accurate. Thus, the spectral shape of the continuum light remained almost unchanged in a brightness range of 4.5 mag, i.e., $V=19.0$–14.5 mag with fluctuations, although a much flatter spectrum was obtained in August, 1984 (Brindle et al. 1986) and a steeper one in December, 1986.

4. Discussion

4.1. Luminosity and Time Scales of Flux Variations

Various observed and z-corrected time scales for the light variation are presented in table 2. If we take $z=1.715$, $V=14.45$ and the spectral index of 1.85, and assume no interstellar absorption in our Galaxy, the total luminosity in the frequency range of 3×10^{13}–10^{15} Hz is calculated as $L=4.2\times 10^{49}$ erg s^{-1} with $H_0=50$ km s^{-1} Mpc^{-1} and $q_0=1$. Also, if we consider the case for August, 1984, i.e., $V=14.0$ mag and $\alpha=1$, it still amounts to 1.7×10^{49} erg s^{-1}. If we assume $H_0=100$ instead of 50, L decreases by a factor 4, but it is still about 10^{49} erg s^{-1}. Also, if we assume $q_0=0$, then L increases by a factor of $(1+0.5z)^2=3.5$. Other constraints for the above estimate of L may be related to the frequency range for the integration and the constancy of the spectral index within the adopted range of frequencies for the integration. However, these factors do not seem to affect the derived luminosity seriously, since the flux has increased certainly in other frequency regions. In 1985 M. Inoue and T. Kato (private

Table 2. Rates of changes in V magnitudes and polarization angles.

Period	Range of variation	Rate (obs.)	t (1/2; obs.)	t (1/2; source)
		(a) V magnitude		
1984–11–05 to 12–27	1.60 mag	$+0.037\pm 0.000$ mag d^{-1}	20.3 d	7.5 d
1985–01–14 to 02–20	1.15	-0.027 ± 0.001	27.9	10.2
1984–12–17 to 12–20	0.23	$+0.075\pm 0.002$	10.0	3.7
1986–11–01 to 12–06	2.5	<-0.069	<11	<4
		(b) Polarization angle		
1984–10–25 to 12–23		$+0.89\pm 0.02$ deg d^{-1}		
1985–01–14 to 02–20		-2.72 ± 0.20		
1984–12–23 to 02–20		-3.85 ± 0.18*		
1984–12–23 to 12–27		-3.06 ± 0.61		
1984–12–27 to 01–14		$+4.0$		
		-6.0*		

* In these cases, the change in polarization angles during December 23 and January 14 is interpreted as 108° instead of 72°.

communication) observed an increase of the radio flux at 10 GHz by a factor of more than 2 compared with the spectrum reported by Gaskell (1982) and Blades et al. (1982a). Thus, the bolometric luminosity, which should be considered in the discussion, will not change appreciably, even if the above situations partially hold. On the basis of the considerations mentioned above, we may conclude that the luminosity exceeds by at least 10^{49} erg s^{-1}. The luminosities of distinct outbursts in other blazars are estimated to be less than 10^{48} erg s^{-1} (O'Dell et al. 1978; Puschell et al. 1979; Wills et al. 1983). Only the luminosity in the outburst of 4C 29.45 in 1985 might exceed 10^{49} erg s^{-1} (W. Z. Wiśniewski, *IAU Circular*, No. 4057, 1985). The luminosity of PKS 0215+015 observed in the 1984–85 burst is undoudtedly the largest recorded in the photometric history of blazars.

As we see in table 2, the minimum time scales for the 50% variation of the fluxes are 3.7–10 d in the frame associated with the source. The combination of this time scale and the luminosity derived above exceeds the limit for the validity of the isotropic emitting model studied by Elliot and Shapiro (1974), even if we take $H_0=100$ and $q_0=1$.

The enormous luminosity means that, if this luminosity corresponds to the Eddington luminostiy, the mass of the central engine responsible for the increase of the radiation will be greater than $10^{11}M_\odot$ which is comparable to that of normal galaxies. It is hardly acceptable as the mass of a central black hole of even the giant elliptical galaxy usually considered as an underlying galaxy of a BL Lac object. However, Abramowicz et al. (1980) have shown that a thick accretion disk can have luminosities 100 times above the Eddington limit. This means that a much smaller mass for a central engine is possible.

Abramowicz and Nobili (1982) also studied along the line of Elliot and Shapiro (1974) taking account of the rotation of the accretion disk surrounding the black hole, and found that the limit was relaxed by a factor of about 20. In our results, no case is found in which the relation by Abramowicz and Nobili (1982) does not hold with the assumptions of $H_0=50$ and $q_0=1$. Also, Impey et al. (1982) and Bassani et al. (1983) compared the relation by Abramowicz and Nobili (1982) with the published observations and obtained similar conclusions. Thus, a jet or something related to it such as the acceleration of high-energy particles at shock fronts (e.g., Marsher and Gear 1986; Biermann and Strittmatter 1987) is responsible for the observed behavior in PKS 0215+015.

4.2. *The Amount of Variations in Polarization Angles*

Under the assumption of isotropic emission from a source, the observed variation in the polarization properties and wavelength dependence of polarization in blazars have been explained rather successfully by the two-component model, which is the simplest one among multicomponent models. The two-component model explains the variation of polarization by the variation of the relative strength of fluxes of two sources which have independent but constant polarization levels and angles.

If the simple two-component model holds, the track of variation of the Stokes parameters is expressed by a straight line in the *IQU* space. However, as shown in figure 4, the behavior on the *QU* plane is different from that expected by the two-com-

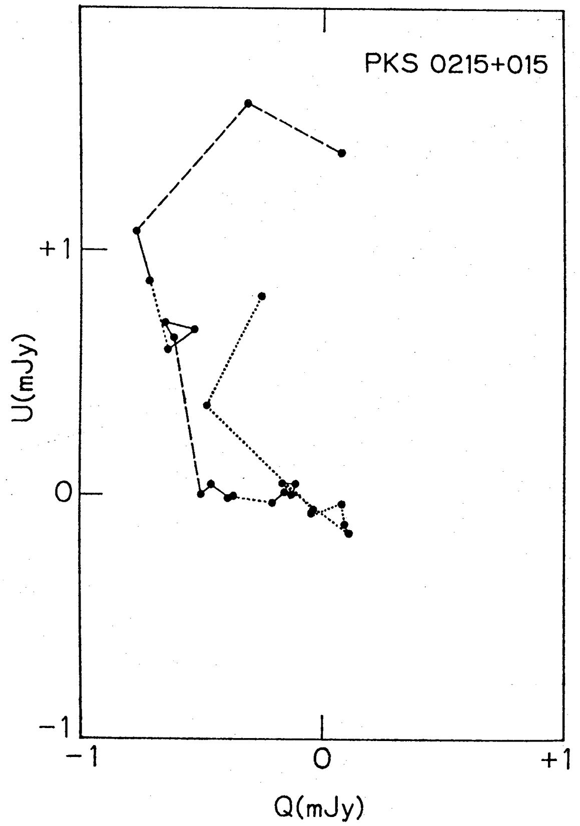


Fig. 4. The behavior of Stokes parameters Q and U in PKS 0215+015. The data obtained with an interval of one day, less than three days, and greater than three days are combined by the solid, dashed, and dotted lines, respectively.

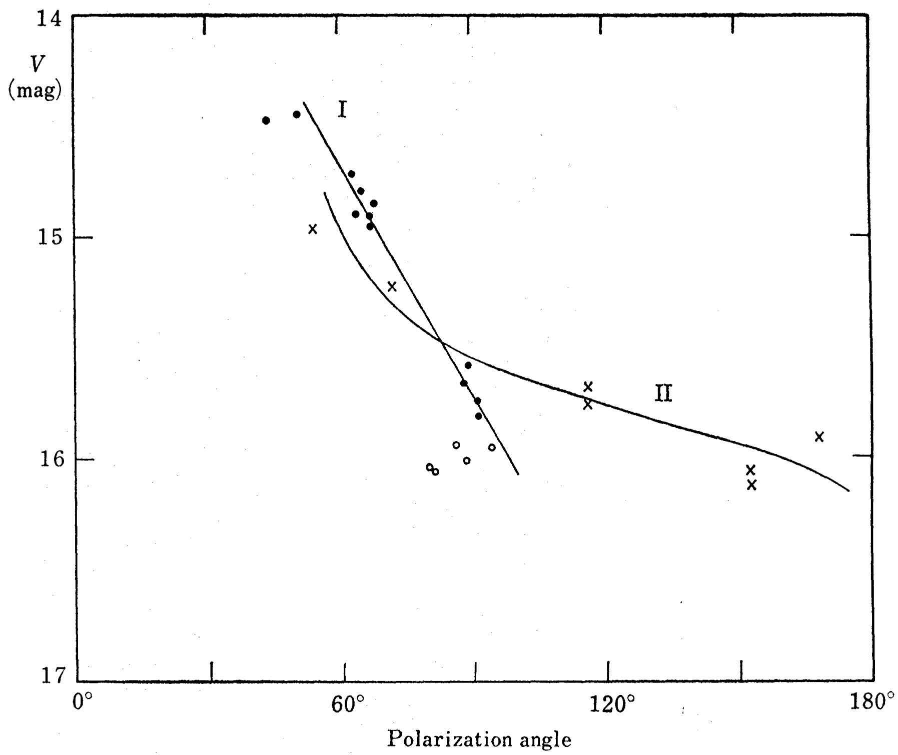
ponent model. Similar situations are seen on the IQ and IU planes.

The simple two-component model predicts that the amount of variations in polarization angle should be less than 90°. The observed swing of polarization angle between January 14 and February 20, 1985, however, is about 100° which exceeds the limiting value of the two-component model. Björnsson (1982) showed that a variation of polarization angle over 90° is possibly explained by the aberration effect of a relativistically moving cloud in an axially symmetric distribution of magnetic field.

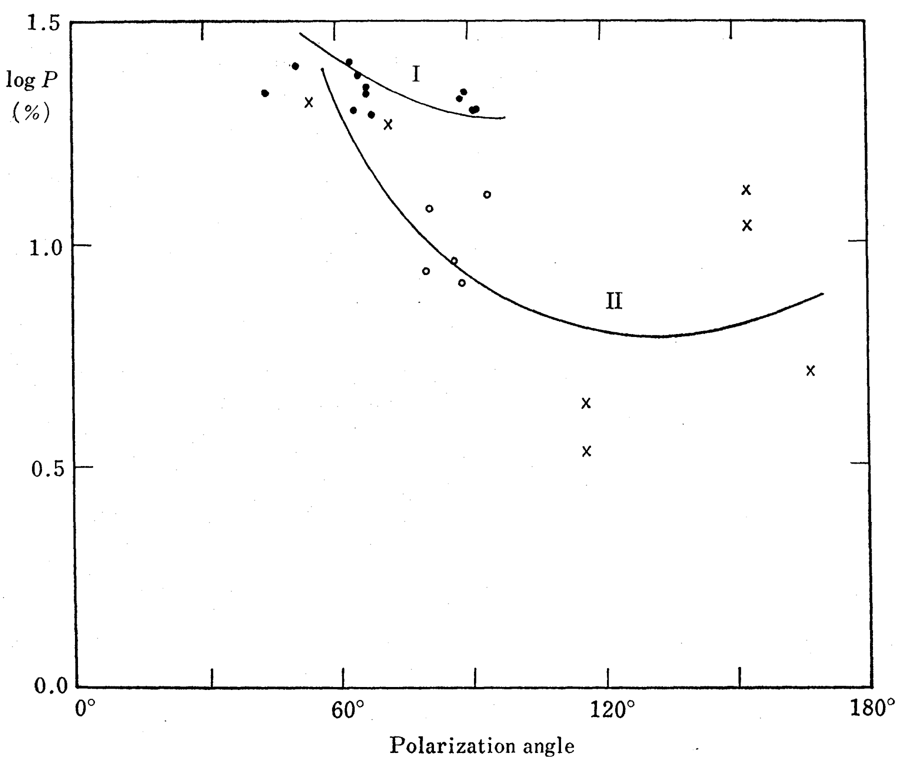
It should be lastly mentioned that the rotation of the source can explain the polarimetric behavior, since aberration plays basically the same role as rotation.

4.3. *A Possible Explanation by the Beaming*

In the previous subsections, we have shown that the photometric and polarimetric behavior in PKS 0215+015, especially in 1984–85, cannot be interpreted by a simple isotropic emission source. Blandford and Königl (1979) explained successfully the radio behavior in terms of a jet but said little about the optical emission. However, the explanation for the rapid variation of polarization angle is applicable to that in other wavelength regions. Although many kinds of studies for optical emission should be done, we try to explain the variations in both the flux and polarization properties at the same time with a simple beaming mechanism. This means that an intrinsic life time of a single flare is much longer than the characteristic time scale of the ob-

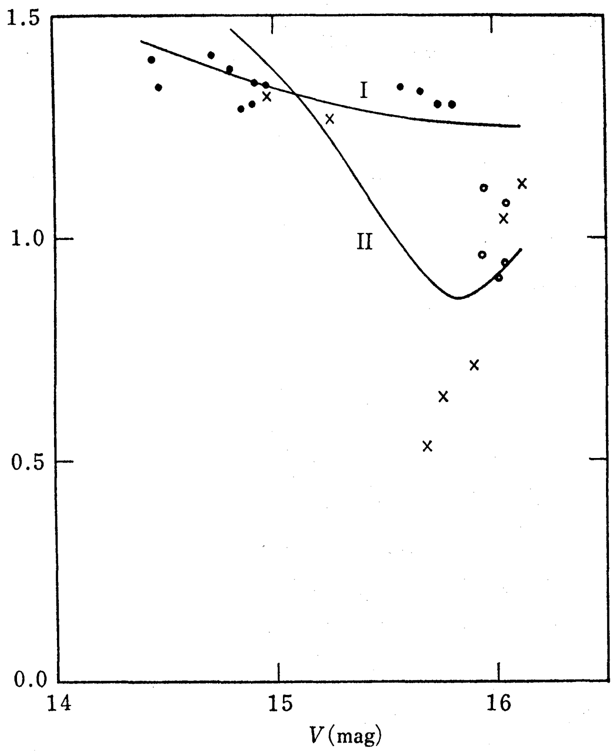


(a)



(b)

Figs. 5a and b. See the legend on the next page.



(c)

Fig. 5. Results of a test calculation for a relativistically moving source in an accelerated or deccelerated state for the long-term trends in 1984–85. The curves for the first and second halves of the observing period are labeled by I and II, respectively. The observed points for the first and second periods are shown by filled circles and crosses. Open circles are the data obtained in December 23–27, 1984, i.e., an intermediate epoch between the first and second periods. The viewing angle in the observer's frame is assumed to be 4°, and the angle between the direction of the bulk motion and that of the magnetic field, ξ, is 45° in a comoving frame for both cases. The azimuthal angles, η, for I and II are 30° and 5°, respectively. The azimuthal angle is measurd from an intersection of a plane perpendicular to the line of sight and a plane which contains the vectors of the bulk motion and the line of sight. For details of the coordinates, see Björnsson (1982). The relation between the variations of flux and polarization angle seems almost satisfactory as in figure 5a, while those related to polarization level are rather unsatisfactory as in figures 5b and 5c.

served variations. In other words, the reacceleration and/or more or less continuous injection of high-energy electrons are occurring in the source, since the life time of high-energy electrons responsible for the observed optical emission is much shorter than the time scale of the observed variations.

If the observed variation is mainly caused by the aberration effect, the Doppler factor $[D=(1-v^2)^{1/2}(1-v\cos\theta)^{-1}]$, where θ is the viewing angle, i.e., the angle between the direction of the motion and the line of sight, and v the velocity in units of the speed of light, should be larger than $(1+z)=2.715$, since the observed time scale is related to that in the source as $\Delta t(\mathrm{obs})=\Delta t(\mathrm{source})(1+z)/D$. Thus, it seems reasonable for the Doppler factor D to be about 10 or more. This means that the relation of $\sin\theta<1/D$, i.e., the viewing angle is less than about 6°, if we consider only the case where a cloud is approaching the observer.

Björnsson (1982) extensively studied the polarization properties due to a relativistically moving source emitting synchrotron radiation mainly from the viewpoint of kinematics. Following Björnsson's (1982) study, we made test calculations to find a possible set of parameters which explain the observations. The present calculations were made, assuming also the configuration of the magnetic field to be axially symmetric. In the present calculations, we assume the viewing angle, θ, to be 4°, and consequently the maximum Doppler factor should be 14.3. We assume that the Doppler factors at the light maxima in November, 1984 and late February, 1985 are around the maximum value. Changing the other two parameters for the direction of the magnetic field, i.e., the angle between the direction of the symmetric axis of the field structure and that of the bulk motion ξ, and the azimuth of the symmetric axis η, we try to find a possible set of parameters which explain the observations.

An example of the results of test calculations is given in figures 5a–c. In the case for $\xi<50°$, the variations in flux and polarization angle are satisfactory for the long-term trend. However, the explanation for the variation in polarization level is not sufficient. The test calculation shows that the angle ξ is not close to 0° or 90°, i.e., it is in an intermediate range, provided that the viewing angles in the comoving frame at the light maxima are close to 90°. Also, the polarimetric behavior depends greatly on η as pointed out by Blandford and Königl (1979).

In the calculation, the flux variation was estimated to be $D^{3+\alpha}$, which means that the spectrum is of the power-law type with a spectral index of 1.85. Under the situation given in figures 5a–c, the size of the emitting region in the comoving frame is larger than 0.03 pc, and no problem associated with the high photon density arises.

For the case of a homogeneous synchrotron source, the polarization level is expressed as $P=(\alpha+1)/[\alpha+(5/3)]$, where α is the spectral index. The observed maximum polarization is about 25% in 1984–85, and therefore, depolarization, probably due to the imcompleteness of the field alignment, by a factor of about 3 occurred in the strongly polarized state.

Lastly, we have to mention that, along this line of consideration, the variation in polarization angle never exceeds 180°, and a possible case for the 220° variation is not explained.

4.4. *The Variation in Polarization Angle over 180°*

There is a possibility that the position angle has varied over 180° as stated in subsection 4.2. Large swings of polarization angles were also observed in other blazars. Ledden and Aller (1978, 1979), Altschuler (1980), and Aller et al. (1981) found large swings of polarization angles in the high-frequency radio region in several compact radio sources, although no such variation was detected at 2.7 GHz (O'Dea et al. 1983). In some cases, the swings of polarization angle exceed 180°. Also, in OJ 287 Kikuchi et al. (1988) found a very rapid and synchronous variation of polarization angles both in the optical and radio regions. The amount of the swing possibly was over 180° and followed by a swing-back.

Königl and Choudhuri (1985a, b) studied the equilibrium configuration of the magnetized plasma in the relativistic jet and pointed out that the variation of the polarization angle over 180° is possibly explained by the progressing illuminated radiation due to shock waves in the nonaxially symmetric (e.g., helical) magnetic field. If large swings both less and more than 180° are caused by a common mechanism, the situation indicated by Königl and Choudhuri (1985a, b) becomes more likely. It seems suggestive that the polar angle of the magnetic field of 45° in the test calculation in the previous subsection has explained photometric and polarimetric behavior. Also, a case like in OJ 287 in which a large swing of polarization angle followed by a swing-back seems to be interpreted by the variations of pitch angle with the distance from the central engine (Kikuchi et al. 1988). In this context, Jones et al. (1985) explained the variations of polarization angle including the cases for the variations over 180° by the results of random walks. It is interesting whether the flux variation for PKS 0215+015 in 1984–85 is also interpreted similarly by random walks.

4.5. *Relation between the Polarization Level and Angle*

According to Björnsson (1982), both the simple two-component and the beaming models predict that a state of low polarization is always associated with a large swing of polarization angles. During January 14–February 20, the polarization angle varied quickly, and polarization seems to have a minimum strength in late January. This feature of the polarimetric variations is just as expected by both models. On the other hand, no such feature on a similar time scale was observed during the first half of the observing period. However, if we look carefully the behavior of polarization levels, we notice that the change of the polarization level has also occurred rather abruptly as seen in figure 1c. Rapid decreases and recoveries of polarization on a time scale of a few days were observed around November 10 and December 25, 1984. Especially in the latter period, the position angle varied very rapidly, although, in the former, the variation of the position angle was not evident. It should be also noted that the flux and colors have shown a systematic change in the latter period. If we look only at the polarimetric behavior around the latter period, the prediction by both models is satisfied. However, in general, the relation between the polarization angle and the polarization degree is not as clear as expected.

4.6. *The Spectral Shape*

Cruz-Gonzalez and Huchra (1984) studied the energy distribution of BL Lac objects and pointed out that the break at high energy occurs almost always between 14.0 and 15.0 in the logarithmic frequency. As the redshift of PKS 0215+015 is 1.715, the optical frequency in the observer's frame corresponds to 15.0–15.5 in the logarithmic scale in the rest frame. Therefore, it is probable that the spectrum is much flatter in the near-infrared region. In fact, Impey and Neugebauer (1988) showed that the averaged spectrum of PKS 0215+015 has a high-energy break at about $\nu=10^{14.5}$ Hz in the rest frame.

The spectral index remains almost unchanged around 1.85 in the brightness range of V=19.0–14.5 mag. In the brightest state, however, a much flatter spectrum of $\alpha\sim1$ was observed (Brindle et al. 1986). It is possibly interpreted that, at this epoch, the high-energy break is present at a frequency higher than the optical one. In future observations, we should pay a particular attention to the shape of the energy distribution.

In this context in OJ 287 the color-luminosity relation has been found in the ultraviolet through to the near-infrared region [Hanson and Coe (1985); Gear et al. (1986); also unpublished data by the author]. It was occasionally observed that the flux increased as the spectrum became flatter after the 1983 outburst. Hanson and Coe (1985) explanied the color-luminosity relation in OJ 287 after the 1983 outburst as a result of a change of the energy distribution of injected electrons. However, the case in PKS 0215+015 is not so simple, since the colors became redder when the source rapidly brightened in December, 1986.

4.7. Wavelength Dependence of Polarization

The wavelength dependence of polarization level was occasionaly found in the present study, but no case for polarization angle. For OJ 287, Kikuchi et al. (1976) and Holmes et al. (1984) observed that both the polarization level and the polarization angle depended on wavelength. Similar results were also occasionally obtained for other BL Lac objects (Tapia et al. 1977; Rieke et al. 1977; Knacke et al. 1979; Puschell et al. 1979, 1983; Puschell and Stein 1980; Impey et al. 1982; Sitko et al. 1984). According to Puschell et al. (1983) and Sitko et al. (1984), the contamination of unpolarized light or simple Faraday rotation is not likely the origin of the observed wavelength dependence of polarization. Some of the observations are interpreted by the two-component model, i.e., by two independent clouds, one is rather stable and another is highly variable in both polarization level and angle (Kikuchi et al. 1976; Holmes et al. 1984; Brindle et al. 1985).

From a theoretical side, Nordsieck (1976), Björnsson and Blumenthal (1982), and Björnsson (1985) studied the wavelength dependence of polarization through the relation between the polarization properties and the spectral shape. However, using the observational data of PKS 0215+015, we find no definite relation between the wavelength dependent polarization and colors, i.e., $U-B$, $B-V$, and $V-R$, except the one during a short period. The relation found on a short time scale is in the opposite sense to the theoretically predicted ones.

5. Conclusions

The principal results in the present study are summarized as follows:

(1) The range of the flux variation is at least 5.0 mag in the V region.

(2) The luminosity exceeds 10^{49} erg s^{-1} for the isotropic emission model, if we take $V=14.45$ mag, $\alpha=1.85$ ($F_\nu \propto \nu^{-\alpha}$), and $z=1.715$.

(3) The time scales of the 50% flux variation are observed to be a few to about ten days. The relation between the luminosity and the time scales of the flux variation exceeds the limit for an isotropic emission source of Elliot and Shapiro (1974), but almost holds within the limit by Abramowicz and Nobili (1982) which takes into consideration the effect due to the beaming and/or the rotation of the accretion disk.

(4) The polarization angle showed large swings of about 50° and 100° during the first- and second-half of the observing periods in 1984–85, respectively, suggesting the aberration effect due to the relativistic motion of the source. The directions of the

swings of the polarization angle in both periods were in oppostie senses. There is also a possibility that the swing during the second-half period in 1984–85 amounted to 220°.

(5) On the basis of the facts mentioned in (2)–(4), we conclude that beaming is responsible to explain the observations. It is the first case in the optical region where relativistic beaming is supported on both photometric and polarimetric bases at the same time.

(6) There are cases where a state of low polarization is associated with the large swing of the polarization angle as Björnsson (1982) has predicted for both the simple two-component and beaming models.

(7) For the case where the aberration effect due to a relativistically moving cloud is dominant, the Doppler factor is regarded to be about 10 or more and the viewing angle is less than about 5°. The direction of the magnetic field is neither perpendicular nor parallel to that of the bulk motion.

(8) If the amount of the variation in polarization angle exceeds 180°, it is likely that the illuminated radiation by shock in the nonaxially symmetric magnetic field plays an important role.

Besides more quantitative studies on the above discussion, the following problems, however, still remain in the interpretation by beaming in the field of photometry and polarimetry:

(1) The details of the large swing of polarization angle are still uncertain because of the lack of the number of observations.

(2) The relation between polarization level and angle is not so clear.

(3) The explanations for the wavelength dependence of polarization and for the relation between the polarization and the spectral shape are not satisfactory.

At the present stage, it is important to compare the observational data with the theoretically expected features which are simplified to express the properties of the photometric and polarimetric behavior. For further interpretation, we should take into account of the dynamics of the source, the configuration of the magnetic field, and other factors such as the deviation from a power-law distribution of high energy electrons.

From the observational viewpoint simultaneous observations of various kinds in a wide range of wavelengths as well as continuous monitoring with photometry and polarimetry are desired for further understanding of the physical processes in active galactic nuclei.

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