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Optical and UV observations of the BL Lacertae object PKS 2155-304*

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Abstract. The BL Lac object PKS 2155-304 has been monitored in two subsequent observing campaigns within three weeks in June 1990 and during another run in September 1994 at optical wavelengths. During the first part PKS 2155-304 showed night-to-night variations of a few percent, whereas in the second part no variability could be detected. During the third run PKS 2155-304 showed variations similar to those in the first campaign. We did not detect any variations on time-scales shorter than one day. The object was in a bright state during the observations in June 1990 ($m_V \sim 12.7$) and close to its historical maximum brightness in September 1994 ($m_V \sim 12.3$). The observations imply that even objects with a high duty cycle and a well known history of rapid variability may be quiescent over longer periods. The power density spectra are not constant at high frequencies (time-scales shorter than a few days) and are not related to the average brightness level at a particular epoch. Comparison with IUE spectra in June 1990 show that PKS 2155-304 was also very bright in the UV. During that period we found an indication that the optical-UV spectral index steepens, when the source became brighter, whereas usually the opposite is observed.

Key words: BL Lacertae objects: general – BL Lacertae objects: individual PKS 2155-304

1. Introduction

The BL Lac object PKS 2155-304 is one of the brightest objects of its class in the optical, UV and X-ray regimes. It was identified as a BL Lac object by its strong, variable X-ray emission with HEAO 1 (Schwartz et al. 1979). It is highly variable in the total optical flux (e.g. Griffiths et al. 1979, Miller & McAlister 1983, Hamuy & Maza 1987, Carini & Miller 1992) and the polarized light (Griffiths et al. 1979, Luna 1986), in the UV (e.g. Urry 1986, Edelson et al. 1992) and in X-rays (e.g. Snyder et al. 1980, Morini et al. 1985, Treves et al. 1989). The typical time-scales measured so far are several minutes up to hours in the X-ray and days to weeks in the UV and optical. Within these time-scales the amplitudes of the variability reach up factors of 2 and 5 in the X-ray, UV and in the optical, respectively. Additionally it has a featureless optical continuum (Griffiths et al. 1979). Recently it was detected in $\gamma-$rays by EGRET (Vestrand, Stacy & Sreekumar, 1995).

Spectra taken of the faint nebulosity associated with PKS 2155-304 gave a redshift of z = 0.117 (Bowyer et al. 1984). This redshift is probably due to a galaxy displaced by about 4" to the east from the BL Lac (Falomo et al. 1991). However, more recent spectroscopy of the faint nebulosity ($\sim$ 3" west of the nucleus) presented by Falomo et al. (1993) revealed a redshift of z = 0.116, fully consistent with FUV spectroscopy presented by Appenzeller et al. (1995) and Bruhweiler et al. (1993), who identified several intervening Lyα absorption systems up to redshifts of $z_{abs} = 0.106$.

Since a few years attempts are made to measure variations on short time-scales in the optical. Detailed investigations showed that a large fraction of BL Lac objects is variable on time-scales of hours to days (e.g. Wagner et al. 1990, Carini 1991, Xie et al. 1991, Heidt & Wagner, 1996, Heidt, 1997) with high duty cycles. Variability on such short time-scales in the optical regime has been reported for PKS 2155-304 by Carini & Miller (1992).

Simultaneous monitoring in different energy bands is an important means of studying the physical processes in BL Lacertae objects. The time- scales in the various frequency regimes pose constraints on the sizes and relative locations of different constituents. In the absence of sufficient spatial resolution in direct observations, variability studies are unique in testing models of the central structure in these AGN.

The rapid changes in flux density of BL Lac objects have mostly been investigated within two different frameworks (Wagner & Witzel, 1995). The putative accreation disks are a possible site. Hot spots or other inhomogeneities lead to fluctuations, as suggested e.g. by Wiita et al. (1991). Alternatively, shocks within the jets of BL Lac objects which are suggested to point towards the observer, may cause variability, as discussed e.g.

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by Marscher & Gear (1985) or Camenzind & Krockenberger (1992). In addition, external causes, such as gravitational microlensing may play a role. In general, different models predict different spectral characteristics of variability. It may also be possible that several mechanisms occur within a single system. Disentangling these cases is even more challenging.

PKS 2155-304 is a very prominent AGN with very rich characteristics in its variability pattern and its variations have been suggested to be due to all of the above models. Treves et al. (1989) found that the overall spectral variability of PKS 2155-304 is well described by the standard synchrotron self-Compton (SSC) model for an inhomogeneous source. Miller et al. (1991) found simultaneous variability in the optical and UV. They were able to explain them by flares or hot spots from an accretion disk (Wiita et al. 1991). On the other hand Edelson et al. (1991) found that at least the UV emission in PKS 2155-304 was not radiated from an accretion disk, since the time-scales of the variability did not match the expectations within the models of a standard accretion disk.

Finally, the results of two large multi-wavelength monitoring campaigns (Nov. 1991 and May 1994, see Edelson et al. (1995) and references therein; Pesce et al. (1997), Pian et al. (1997)) showed that PKS 2155-304 may display a very different behaviour. Whereas recurrent flares on time-scales of ≈ 0.7 days dominated in November 1991, its variability was characterized by two large outbursts in May 1994. The different patterns clearly illustrate our poor knowledge about the "typical" behaviour of even the brightest and best studied sources. In particular, it is still unclear whether variability characteristics on short time-scales are related to spectral changes or the general brightness level.

Here we present our observations of two subsequent runs in the optical of PKS 2155-304 in June 1990, which we combine with IUE spectra taken during that period as well as a search for microvariability in the optical taken in early September 1994.

2. The data

2.1. Optical observations and data reduction

The observations in 1990 were obtained at ESO, La Silla, Chile from June 12 until 16 and June 25 until July 1. For the first sequence the MPG 2.2m telescope and the Danish 1.54m telescope were used. The observations at the 2.2m telescope were carried out by Drs. O. Hainault, B. Jarvis and T. Richtler and at the 1.54m telescope by Dr. F. Fusi Pecci. They kindly spend some hours each night on this object during their observing runs. Both telescopes were equipped with an RCA CCD in order to perform relative photometry. During this part standard Bessel V and R-filters were used. In the second sequence we used only the Danish 1.54m telescope, an RCA CCD and Bessel R-filter. At the 2.2m telescope a scale of $0\farcs35$/pixel provided a field of $2' \times 3'$. At the Danish telescope the field of view was $2\farcm5 \times 4'$ with a scale of $0\farcs471$/pixel.

The observations in 1994 were also obtained at ESO, La Silla, Chile from August 29 until September 3. Here the Danish 1.54m telescope equipped with a TEK 1k CCD and Bessel R-filter was used. With a scale of $0\farcs388$/pixel our field of view was $6\farcm4 \times 6\farcm4$.

Table 1. Results of the fits to SWP and LWP spectra of PKS 2155-304 taken between October 1989 and November 1990.

Image number	Date (J.D.) (2440000+)	F(mJy)	α
SWP 37451	7824.42	8.14±0.33	−0.57±0.22
SWP 39024	8049.55	15.58±0.06	−0.41±0.02
SWP 39032	8050.53	16.85±0.07	−0.32±0.02
SWP 39090	8056.94	12.82±0.04	−0.47±0.02
SWP 39091	8057.04	12.65±0.06	−0.63±0.03
SWP 39092	8057.13	12.83±0.06	−0.52±0.02
SWP 39099	8059.95	14.40±0.05	−0.50±0.02
SWP 40056	8201.36	7.27±0.04	−0.67±0.03
LWP 18047	8049.61	23.16±0.10	−0.46±0.03
LWP 18054	8050.47	24.66±0.12	−0.37±0.03
LWP 18102	8057.00	19.68±0.10	−0.47±0.04
LWP 18103	8057.08	19.44±0.13	−0.54±0.05
LWP 18115	8060.00	22.40±0.14	−0.60±0.04
LWP 19124	8198.83	10.06±0.16	−0.66±0.11
LWP 19155	8201.40	11.02±0.25	−1.00±0.16

The CCD frames were bias subtracted and flat-fielded using domeflats and twilight frames in order to correct for the pixel-to-pixel variations of the CCD. For relative photometry the fluxes of PKS 2155-304 and several comparison stars were measured on every frame. The flux of PKS 2155-304 and star Nr. 5 given by Hamuy & Maza (1989) as comparison star on each frame were divided and the mean value of this ratio from all frames computed. If star Nr. 5 was not on the frame we scaled the flux of the comparison star 6[1] ($65''$ NNE of PKS 2155-304) of this frame by averaging the ratio of star Nr. 5 and star Nr. 6 on > 50 frames where both stars are present to the flux of star Nr. 5. Star Nr. 6 is $\approx 2.80\pm0.09$mag fainter in V and $\approx 2.62\pm0.07$ in R than star Nr. 5.

The lightcurves of the normalized ratios are shown in Fig. 1. The same procedure has been carried out for all of the field stars. The photometric errors were computed from the scatter of the normalized ratio of the comparison stars. For our data taken in June 1990, the error was 1.1% when star Nr. 5 could be used, which was about 2.5 magnitudes fainter as the BL Lac object and was up to 6%, when star Nr. 6 could be used. Star Nr. 6 was about 5mag fainter than PKS 2155-304. Due to the larger field of view during our observations in September 1994, which allowed us to use comparison stars of similar brightness as PKS 2155-304, the photometric errors are about 0.6%. The exposure times had been chosen such that the errors are independent of

[1] A finding chart for star Nr. 6 can be found under http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts.html

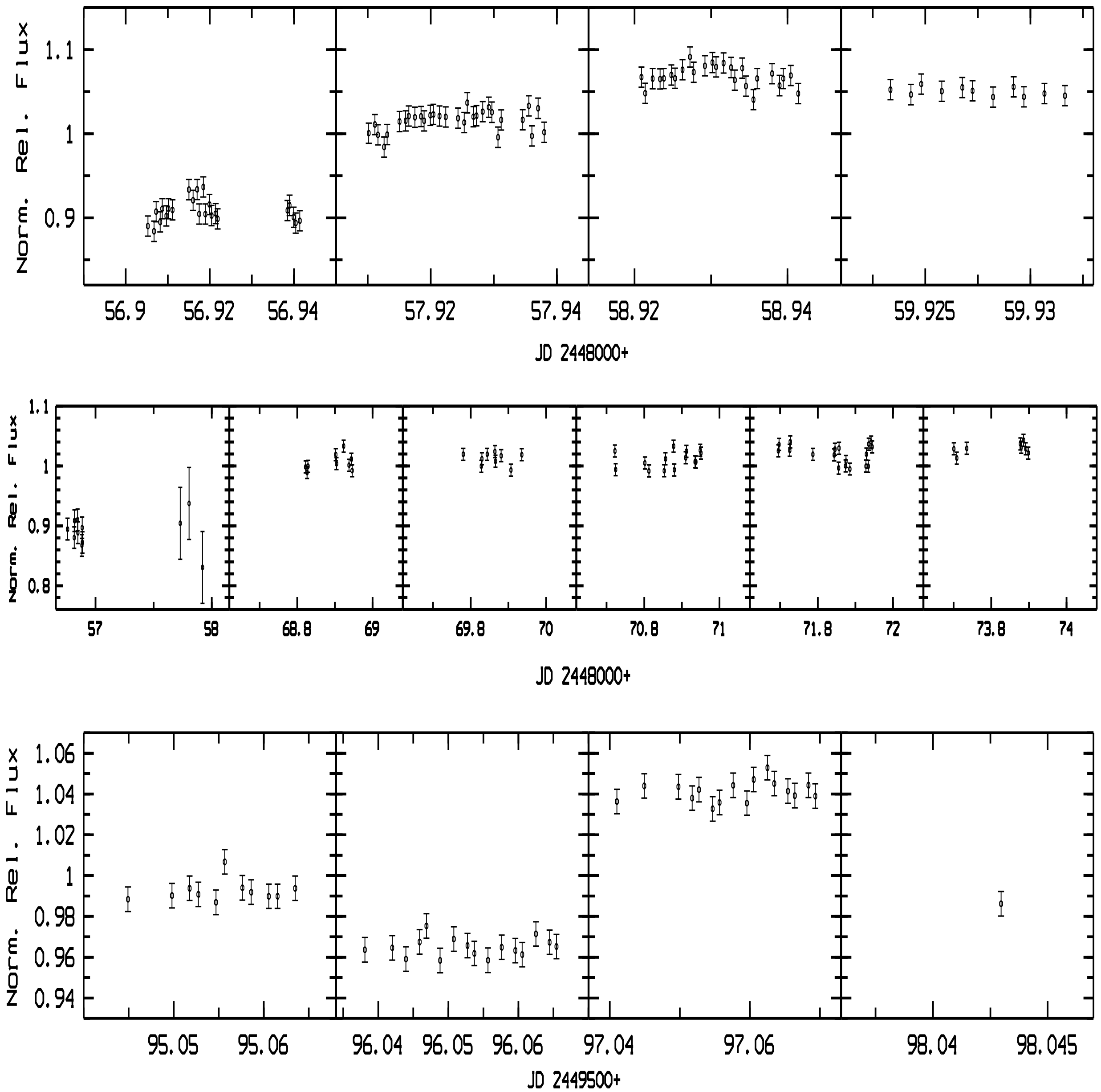

Fig. 1. Lightcurves of PKS 2155-304 observed during the three observing runs. Each diagram contains the observations obtained during a single night. Top: Lightcurve of PKS 2155-304 in V band from the first observing run in June 1990. Middle: Lightcurve of PKS 2155-304 in R band from the second observing campaign in June 1990. The R band data from the first run are included. Bottom: Lightcurve of PKS 2155-304 in R band observed during the third run in September 1994.

the telescope and the filter used. Since not all frames contain the same comparison stars, different accuracies for individual frames were obtained.

In spite of mostly non-photometric conditions, photometric calibration was performed with star Nr. 5 in the field of PKS 2155-304 given by Hamuy & Maza (1989). This star has an V magnitude of 15.35±0.03 and a color index V-R of 0.34±0.01.

2.2. The IUE data

IUE spectra collected between Oct 1989 and Nov. 1990 were retrieved from the Uniform Low Dispersion Archive (ULDA, Wamsteker et al., 1989). The flux-calibrated spectra were converted to mJy and dereddened following Urry et al. (1993) using the extinction curve from Seaton (1979) and assuming E(B-V) = 0.034 mag.

In order to derive fluxes and spectral indices for our UV data we fitted a power-law of the form $F(\nu) = F_0 \cdot (\nu/\nu_0)^{\alpha}$ to the spectra, where the normalization was 1400 Å for the

SWP and 2800 Å for the LWP spectra. The fitting procedure was carried out in log(F(ν)) - log(ν) space which resulted to the use of a simple 1st order polynomial of the form log(F) = log(F_0) + $\alpha \cdot \log(\nu/\nu_0)$. The fit was done over the wavelength range 1230 - 1950 Å excluding the regions 1277-1281, 1286-1290, 1470-1540 and 1660-1666 Å for the SWP (as in Urry et al., 1993) and 2100-3100 Å for the LWP excluding the region 3045-3070 Å (see Edelson et al., 1992).

The resulting fluxes and spectral indices are given in Table 1. We compared the results of our fitting procedure to those given by Edelson et al. (1992) and Shukla & Stoner (1996). Edelson et al. (1992) gave results for the SWP spectra 37451, 39032, 39099 and 40056 and for the LWP spectra 18054, 18115, 19124 and 19155. Shukla & Stoner (1996) used only SWP spectra (apart from SWP 39024 they analyzed also all the SWP spectra presented in this article). Additionally, they gave fluxes for a normalization of 1550 Å instead of 1400 Å as used by us and Edelson et al. (1992), but gave no spectral indices. Both groups did not deredden the spectra. Therefore we carried out the same fitting procedure as described above to the spectra without dereddening and converted the fluxes from our and Edelson fits to 1550 Å. Whereas the fluxes given by Shukla & Stoner and derived by us are in excellent agreement, Edelsons fluxes are systematically higher by about 15% in the SWP range. The LWP fluxes given by Edelson et al. (1992) and derived by us are similar, but his spectral indices are systematically higher, i.e. the spectra are steeper than ours. We believe that this apparent discrepancy is most likely the result of the different extraction procedure of the spectra (IUESIPS used in the ULDA and OPTIMAL used by Edelson et al., 1992).

3. Results

3.1. Optical data

The results are different for the two observing parts in 1990. In the first week PKS 2155-304 varied in total flux between subsequent nights. It showed night-to-night variations between 5% and 10%. This is shown in Fig. 1 (top). No variations on time-scales of minutes were detected during the hours when the observations were taken. Comparison of the data taken in the first night with both telescopes demonstrate that these data sets agree very well.

PKS 2155-304 displayed a different behaviour in the second part. During the five nights no variations between the nights or on shorter time-scales were detected. This is shown in Fig. 1 (middle), where we have included the measurements in the R-band of the first part of our campaign.

During our observations in September1994 PKS 2155-304 showed a variability behaviour similar to the first part in June 1990. It again showed night-to-night variations of typically 5%. As in June 1990, no variations during the observations in each individual night can be seen. The resulting lightcurve is shown in Fig. 1 (bottom).

Table 2. Nightly averaged magnitudes of PKS 2155-304 during the three observing campaigns. The errors include the inaccuracies for star Nr. 5 given by Hamuy & Maza (1989). The photometric errors of our measurements are in most cases much lower.

Date (J.D.) (2448000+)	$< m_V >$	$< m_R >$	Tel.
56.75-56.88	12.81±0.047	12.57±0.036	2.20m
56.90-56.94	12.83±0.034		1.54m
57.91-57.94	12.71±0.033		1.54m
58.92-58.94	12.62±0.032		1.54m
59.92-59.93	12.64±0.030		1.54m
68.82-68.95		12.44±0.034	1.54m
69.78-69.93		12.43±0.032	1.54m
70.72-70.95		12.44±0.034	1.54m
71.69-71.95		12.43±0.034	1.54m
73.70-73.89		12.42±0.031	1.54m
2448500+			
95.05-95.06		12.07±0.033	1.54m
96.04-96-07		12.10±0.032	1.54m
97.04-97.07		12.02±0.034	1.54m
98.04		12.08±0.032	1.54m

Table 2 shows the nightly averages of PKS 2155-304 for all of our observations. The BL Lac varied between 12.62 and 12.81 in V-band and 12.02 and 12.57 in R-band.

From the night on June 14, 1990 during which several measurements in both filters were taken we computed the V-R colour. It is V-R = 0.26±0.059, which is within the range of V-R = 0.3±0.02 given by Hamuy & Maza (1987). That results in a V magnitude of 12.69±0.068 during the second observing campaign. Assuming no colour changes we can conclude that PKS 2155-304 was in equal brightness at the end of the first part and at the beginning of the second part of our observations.

A few weeks before our observations in June 1990 PKS 2155-304 was observed by Carini & Miller (1992) with the IUE satellite. The FES counts of the IUE satellite at that time correspond to m_V = 12.3. The BL Lac object has faded by about 0.4 magnitudes in four weeks.

Pesce et al. (1997) presents the optical data on PKS 2155-304 from the May 1994 campaign including data until mid-November. The BL Lac showed a continuous brightening from May 1994 (m_R = 12.8 to 12.0 at the beginning of September and a final point indicating a fading to m_R = 12.4 in mid-November). His data taken at the same period as ours are in excellent agreement and suggest that PKS 2155-304 reached the maximum of an outburst lasting 4 months at that time.

In a recent paper, Zhang & Xie (1996) presented a historical lightcurve of PKS 2155-304 in V-band including ground-based observations and FES V-band measurements from IUE. Com-

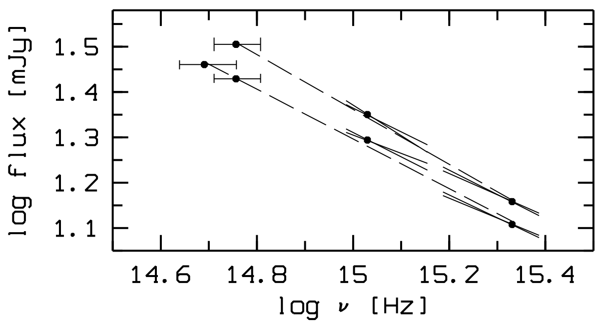

Fig. 2. Multifrequency spectra of PKS 2155-304 from the second part of the first night (low state) and the third night (high state) of the first campaign in June 1990 including the R band measurement taken during the first night. The dahed lines are the best fits through the data points for each individual night. Note the difference in the slopes.

parison with their lightcurve shows that PKS 2155-304 was in a relatively bright state during our observations in 1990. Under the same assumptions given above, our brightest R-band measurement in 1994 (m(R) = 12.02±0.056) converts to m(V) = 12.32. This shows that PKS 2155-304 was about 0.4mag brighter as compared to our observations in June 1990 and as bright as during the observations reported by Carini & Miller (1992). Moreover, it was close to the historically brightest recorded measurement by Carini & Miller (1992).

3.2. The IUE data

The results of our fits show that PKS 2155-304 - within our limited data set - varied by a factor of two in both frequency ranges on time-scales of months. It displayed a low brightness level at the beginning (SWP 37451, Oct 1989) and at the end (SWP 40056/LWP 19155, Nov. 1990) whereas it was brightest on June, 8th (SWP 39032/LWP 18054).

The spectral index α also varied considerably, between -0.32 ± 0.02 and -0.67 ± 0.03 in the SWP and -0.37 ± 0.03 and -1.00 ± 0.16 in the LWP during one year. However, there are also indications for spectral changes on short time-scales, when we compare the spectral indices derived for the spectra SWP 39090-39092 although they are comparable within a three σ level. Such a behaviour can not be seen in the LWP spectra taken during that period (LWP 18102/18103).

4. Discussion and conclusions

Variability measurements of PKS 2155-304 in the optical reported so far display a wide range in patterns. They are ranging from time-scales of minutes with amplitudes of a few percent (Carini & Miller 1992) to night-to-night variations of 10% (Luna 1986), from 30% on time-scales on weeks (Miller & McAlister 1983) to several hundred percent on time-scales of months over the last decade (Zhang & Xie, 1996).

The results from our optical observations can be summarized as follows:

- During the first run in June 1990 and the third run in September 1994 PKS 2155-304 showed night-to-night variations between 5% and 10%. This demonstrates, that such variations, similar to those reported by Luna (1986), also occur during different brightness levels. Especially noteworthy are the results from September 1994, when the object was close to its historically recorded maximum.
- During the second run in June 1990 PKS 2155-304 was completely stable within our accuracy during one week. Such a behaviour has not been seen previously in this source, and illustrates that extended periods of quiescence occur even in the most active BL Lac objects, irrespective of the longterm flux level. It had a comparable brightness to that of the first campaign two weeks earlier.
- We could not detect variations on time-scales of minutes within the errors of our measurements.

These results show that even a well studied BL Lac object with a high duty cycle on time-scales of days may show quiescent stages. The power density spectra are not constant at high frequencies and are not related to the brightness level at a particular epoch. This implies that it is only with sufficiently long, densely sampled observations possible to characterize the variability behaviour of a single BL Lac object.

PKS 2155-304 is the prototype of the so-called x-ray selected BL Lac objects (XBL). It is commonly believed that they are not as strong variable as the classical radio-selected BL Lac objects (RBL) in the optical domain (see e.g. Jannuzi et al., 1993). In a recent study, Heidt & Wagner (1996) and Heidt (1997) determined the intra-day variability properties of the complete 1 Jy sample of RBL as well as of two well defined samples of XBL (the EXOSAT HGLS and EMSS samples) in the optical domain. They found that the duty cycle among both classes differed by about a factor of 2 (0.8 in RBL vs. 0.4 in XBL). Our observations of PKS 2155-304 including the observations by Luna (1986) and Carini & Miller, 1992), who observed PKS 2155-304 in four subsequent nights as well as the results by Smith et al. (1992) and Courvoisier et al. (1995) from the November 1991 campaign lasting four weeks indicate that the duty cycle on time-scales of days is close to, but not exactly unity in this BL Lac. This shows that PKS 2155-304 is an extreme member of the XBL.

Our results of the fits to the IUE spectra of PKS 2155-304 show that the BL Lac varied by about a factor of 2 in both, the SWP and LWP ranges within 6 months. Similar variations, but on shorter time-scales have been detected during the May 1994 IUE campaign on PKS 2155-304 (Pian et al., 1997). It showed also variations of the spectral indices, with an indication of short-term variations in the SWP (image number 39090-39092) in June 1990.

Comparison of our observations with those by Edelson et al. (1992), Urry et al. (1993) and Pian et al. (1997) show that PKS 2155-304 was in June 1990 historically in a very bright stage in the UV band and as bright as during the Nov. 1991 and May 1994 campaigns. Unfortunately, the few data taken at this epoch do not allow to comment on any variations on time-scales of days such that a comparison with the Nov. 1991 and May 1994 data is not possible. During these campaigns PKS 2155-304 displayed a completely different variability behaviour. Whereas the variability behaviour in Nov. 1991 can be characterised by recurrent flares on a time-scale of ≈ 0.7 days, the observations in May 1994 displayed a strong flaring behaviour.

From the campaigns in June 1990, where the observations in the optical and UV are nearly simultaneous (the observations partly overlap), we can calculate the optical - UV spectral indices defined as $\alpha_{\rm UV}^{\rm opt} = \frac{\log({\rm F(opt)/F(UV)})}{\log(\nu_{\rm UV}/\nu_{\rm opt})}$, where the frequencies are set to $2.14 \cdot 10^{15}$Hz for the SWP, $1.07 \cdot 10^{15}$Hz for the LWP and $5.71 \cdot 10^{14}$Hz for the V band, respectively. This was possible for the second part of the first night and for the third night during the first campaign with the corresponding SWP spectra 39090 and 39099 as well as for the LWP spectra 18102 and 18115 (c.f. Tables 1 and 2). The resulting $\alpha_{\rm SWP}^{\rm opt}$ are -0.56 ± 0.04 for the second part of the first night and -0.60 ± 0.05 for the third night. Comparing this result with the brightness in V band (m_V = 12.83 vs. 12.64) there is an indication for a steepening (softening) of the the optical-UV spectrum, whereas usually the opposite (harder when brighter) is observed. The trend is similar also for $\alpha_{\rm LWP}^{\rm opt}$. This is shown in Fig. 2, where we compare the optical-UV data from the two different epochs.

The results of our optical monitoring, the analysis of our UV spectra as well as the comparison of simultaneous optical-UV data clearly show that true simultaneous, sufficiently long observing campaigns with the best possible temporal resolution are necessary to understand the variability behaviour of PKS 2155-304 and the physical processes involved.

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