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MULTIFREQUENCY SPECTRAL BEHAVIOR OF THE BL LACERTAE OBJECTS OI 90.4 AND 3C 66A

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ABSTRACT

We present single-epoch multifrequency data for the BL Lacertae objects OI 90.4 and 3C 66A, spanning radio through ultraviolet wavelengths. Other measurements relevant to intensity and spectral-shape variability are also presented. Both BL Lac objects exhibit spectral curvature in the infrared to ultraviolet region, a property that we infer to be usual for this object class. Variability in the ultraviolet spectral index of OI 90.4 is found, whereas the spectral index of 3C 66A is the same in two observations 17 months apart. We have applied a synchrotron self-Compton jet model to each BL Lacertae object. We find that the OI 90.4 data are best satisfied by a jet with a relatively high degree of relativistic beaming, but emission at frequencies below ~50 GHz is not described by the model. We find that 3C 66A may not always undergo strong relativistic beaming, and the model may incorporate the small fraction of the total radio emission below ~20 GHz that is from within ~1.5 milli-arcsec of the core.

Subject headings: BL Lacertae objects — radiation mechanisms

I. INTRODUCTION

This paper reports further results in an ongoing program of multifrequency observations of active galactic nuclei (AGNs). The program involves spectral measurements of each AGN at radio, millimeter, infrared, optical, ultraviolet, and X-ray wavelengths, made as close to each other in time as possible. The variability time scales of the objects differ, but may be as short as one day in some wavelength bands. We apply models for the structure of AGNs in an attempt to understand our data. Earlier results for BL Lacertae objects are presented by Worrall *et al.* (1982; 1984*a*, hereafter Paper I; 1984*b*, hereafter Paper II). Here we report results for two more BL Lac objects, OI 90.4 (0754+100: Tapia *et al.* 1977) and 3C 66A (0219+428: Wills and Wills 1974). The source OI 90.4 has no measured redshift. Miller, French, and Hawley (1978) tentatively suggest a value of $z = 0.444$ for the redshift of 3C 66A, from an assumed identification of a single weak emission line.

II. OBSERVATIONS

Our multifrequency observations of OI 90.4 were made during 1982 late April and early May, and of 3C 66A during 1983 January and early February. For OI 90.4 and 3C 66A we estimate visual extinctions, A_v, of 0.08 and 0.15 mag, respectively, from Burstein and Heiles (1982). We have corrected all our infrared, optical, and ultraviolet data, using the extinction law of Savage and Mathis (1979).

The dates of our *International Ultraviolet Explorer* (*IUE*) low-resolution, large-aperture-mode observations (Boggess *et al.* 1978) are given in Table 1. The table also lists dates of earlier *IUE* observations of OI 90.4 (Bromage *et al.* 1980) and 3C 66A (Maccagni *et al.* 1983; Chiappetti *et al.* 1982). We gained access to these earlier data through the National Space Science Data Center facility. We then analyzed all the observations using a consistent procedure, described in Paper I. We used the flux-density calibration provided by the Goddard Space Flight Center *IUE* Regional Data Analysis Facility. The spectral parameters in Table 1 were derived from simultaneous fits to binned data from the short-wavelength prime (40 Å bins) and long-wavelength redundant (60 Å bins) cameras.

The 1979 April *UBV* observations of OI 90.4 and all our observations of 3C 66A (Table 2) were made with the No. 2, 0.9 m, telescope at Kitt Peak National Observatory (KPNO) with a 15″.5 diaphragm. The 1982 April measurements of OI 90.4 were made with a 1P-21 photomultiplier, Johnson *UBV* filters, and the Computer Photometer on the KPNO 1.3 m telescope, using a 14″.2 diaphragm. The infrared measurements (Table 3) of OI 90.4 were made with a liquid–helium–cooled InSb detector on the 3 m Shane telescope at the Lick Observatory, with a 7″.5 beam. The observations of 3C 66A used a similar detector on the University of California, San Diego/University of Minnesota 1.5 m telescope on Mount Lemmon, with a 15″ beam.

The sources were both monitored at 4.8, 8, and 14.5 GHz with the University of Michigan 26 m paraboloid (Aller, Aller, and Hodge 1981) for about one month around the time of our *IUE* observations. The total flux-density measurements include both orthogonal planes of linear polarization. The telescope half-power beamwidths (HPBWs) were approximately 10′, 6′, and 3′.2 at 4.8, 8, and 14.5 GHz, respectively. Observa-

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[1] Guest Observer with the *IUE* satellite.

[2] Now with Titan Systems Inc.

TABLE 1

IUE CONTINUUM FITS TO f_ν(Jy) = $K\nu_{15}^{-\alpha}$[a]

Source	Start Time (UT)	Exposure (min)	Camera[b]	α[c]	$K \times 10^3$[d]
		Program Observations			
OI 90.4	1982 May 2 1238	185	LWR	1.52 ± 0.08	1.99
OI 90.4	1982 May 3 0909	400	SWP		
3C 66A	1983 Feb 2 1510	280	SWP	1.58 ± 0.09	1.69
3C 66A	1983 Feb 2 1952	115	LWR		
		Earlier Observations			
OI 90.4	1979 Mar 30 0522	240	SWP	2.08 ± 0.13	1.47
OI 90.4	1979 Mar 30 0939	128	LWR		
3C 66A	1981 Aug 27 1853	280	SWP	1.64 ± 0.07	1.87
3C 66A	1981 Aug 27/28 2337	130	LWR		

[a] The frequency ν_{15} is in units of 10^{15} Hz.

[b] Frequency ranges: SWP: $\nu \approx 1.54$–2.50×10^{15} Hz; $\lambda = 0.12$–0.19 μm;
LWR: $\nu \approx 0.94$–1.54×10^{15} Hz; $\lambda = 0.19$–0.32 μm.

[c] One sigma errors.

[d] Corresponding to best fit value of α.

TABLE 2

OPTICAL OBSERVATIONS

DATE (UT)	MAGNITUDES CORRECTED FOR EXTINCTION[a] V (mag)	B (mag)	U (mag)
		OI 90.4	
1979 Apr 3	14.95	15.41	14.69
1982 Apr 18	15.03	15.56	14.87
1982 Apr 19	14.95	15.49	14.75
1982 Apr 20	15.35	15.83	15.13
1982 Apr 22	15.30	15.81	15.08
	3C 66A		
1981 Sep 21	14.91	15.36	14.79
1981 Sep 25	14.86	15.32	14.76
1983 Jan 19	15.06	15.48	14.94

[a] Errors estimated at ≤0.04 mag. For OI 90.4 we assume $A_V = 0.08$ mag; $A_B = 0.11$ mag; $A_U = 0.13$ mag. For 3C 66A we assume $A_V = 0.15$ mag; $A_B = 0.20$ mag; $A_U = 0.24$ mag.

tions were made with the VLA, in its C configuration, at 4.9 and 15.0 GHz on 1983 February 16 and 17, respectively. The synthesized HPBWs at 4.9 and 15 GHz were ~4″.6 and ~1″.5, respectively. The calibration source was 3C 286, assuming the flux-density measurement of Baars *et al.* (1977). A 20.3 GHz measurement of 3C 66A was made on 1983 January 1 2316 UT with the Owens Valley Radio Observatory (OVRO) 40 m telescope in left-circular polarization. Dual beams of 7′.2 separation were of 107″ HPBW, and beam switching in the azimuth direction followed the pattern described by Birkinshaw and Gull (1984). The noise temperature of the receiver at this frequency was ~40 K. The measurement was repeated on 1983 December 30 0039 UT. The only difference in the procedure was that a symmetrical beam-switching pattern was then employed. Source calibration was with respect to DR 21 and 3C 123 at assumed flux densities of 19.3 and 4.08 ± 0.07 Jy, respectively (Baars *et al.* 1977).

TABLE 3

INFRARED OBSERVATIONS

SOURCE	DATE (UT)	FLUX DENSITY (mJy) 1.25 μm	1.65 μm	2.28 μm
OI 90.4	1982 May 5	13.5 ± 0.8	20.0 ± 1.0	28.0 ± 1.4
3C 66A	1983 Jan 24	8.8 ± 1.2	10.6 ± 0.7	13.1 ± 0.9

III. RESULTS

a) OI 90.4

No ultraviolet line emission or absorption from OI 90.4 was measured in our new *IUE* data. The new and earlier binned data are presented in Figure 1. Our spectral fit to the 1979 March Data (Table 1) agrees with that given by Bromage *et al.* (1980). In 1982 May the intensity was brighter and the spectrum flatter.

The *UBV* color excesses (Table 2) are constant to within measurement errors between the four 1982 April data sets. A power-law fit to the flux densities, $f_\nu \propto \nu^{-\alpha}$, using the calibration of Johnson (1966), renders a mean value of $\alpha = 1.13 \pm 0.05$. There is, however, significant nightly intensity

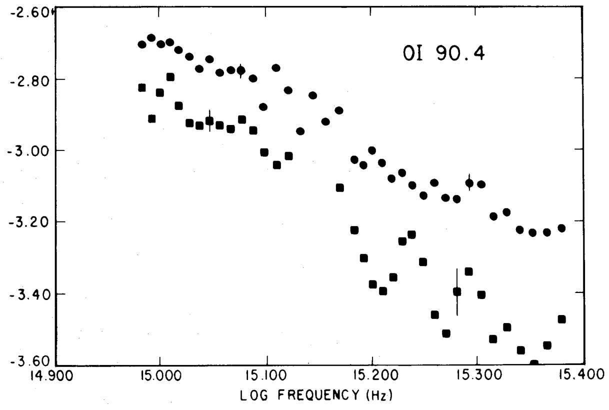

FIG. 1.—*IUE* spectral variability of OI 90.4. Data are from 1982 May (*circles*) and 1979 March (*squares*). Spectral fits are given in Table 1.

variability. Most significant is the dimming by 0.4 mag between April 19 and 20. The fine error sensor of the *IUE* recorded a visual magnitude of 15.0 ± 0.15 mag on 1982 May 2. We have thus plotted the April 18 *UBV* data in Figure 2. The *UBV* measurements for 1979 April imply a best fit value for α of 1.0 ± 0.1, not significantly different from the 1982 April data, despite the change in ultraviolet spectral index.

The infrared flux densities (Table 3) fit $\alpha = 1.24 \pm 0.18$ and are thus consistent with the *UBV* spectral index, but the measurements are ~0.5 mag brighter than expected from extrapolation of the visual spectrum. If, indeed, the spectral shape at visual wavelengths is relatively constant, our results are best explained by infrared flux variability of ~0.5 mag between May 2/3, when the *IUE* observations were obtained, and May 5. The infrared data can also be fitted with an extrapolation from the *IUE* data of index $\alpha \approx 1.38$. For this, either we require a short-time-scale spectral-shape change at visual wavelengths, not suggested by our visual observations, or we reach the conclusion that the spectrum displays wiggles over the infrared to ultraviolet wavelength band. For our discussion in § IV*d*, we shall assume that the source is best represented by a spectrum with $\alpha \approx 1.1$ at infrared and visual wavelengths, with significant intensity, but not necessarily spectral-shape, variability. At ultraviolet wavelengths the index has increased, placing it in a range that spans at least 1.5–2.1.

The radio measurements display an inverted spectrum. The five measurements at 4.8 GHz, eight measurements at 8 GHz, and six measurements at 14.5 GHz, taken between 1983 April 15 and May 18, indicate no significant flux-density fluctuations. They average 1.37 ± 0.08, 1.76 ± 0.02, and 1.97 ± 0.02 Jy for the three frequencies, respectively. Weiler and Johnston (1980) have shown that at 15 GHz only ~0.2 Jy of flux density comes from a source region larger than 0.6 milli-arcsec (mas). We thus assume core emission to dominate our measurements.

We include in Figure 2 the only reported X-ray detection of OI 90.4, which is the 1979 April 27 *Einstein Observatory* measurement of Schwartz, Madejski, and Ku (1982). An extrapolation of our 1982 *IUE* data would fall above the measurement. An extrapolation of the 1979 March 30 *IUE* data, taken only three days later than the X-ray measurement, would fall below the X-ray data point. The *IUE* spectral variability of OI 90.4 leads us to nominate it as a good candidate for an X-ray flux-monitoring program.

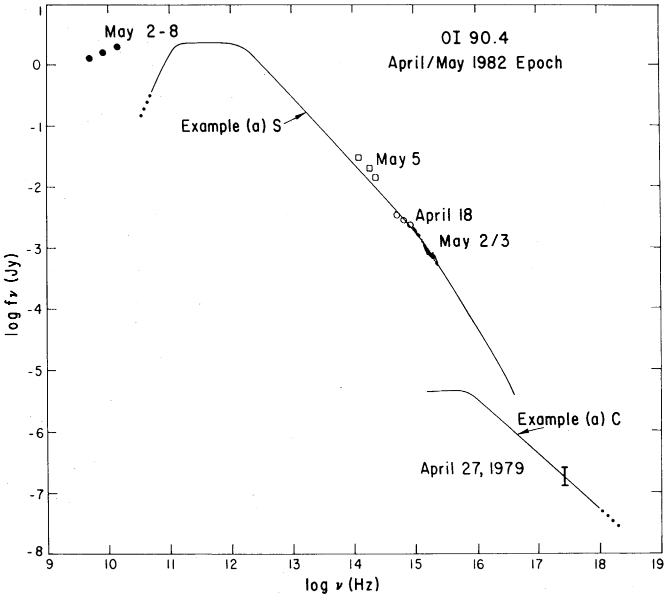

FIG. 2.—Flux densities of OI 90.4 in 1982 April/May. The X-ray measurement is the earlier epoch detection of Schwartz, Madejski, and Ku (1982). The synchrotron (S) and Compton (C) components produced by example (a) in Table 5 are also shown.

b) 3C 66A

As with OI 90.4, no ultraviolet line emission or absorption from 3C 66A was measured in our new *IUE* observations. In contrast to OI 90.4, there was no significant spectral-shape variability between the earlier and new data (Table 1). Our spectral fit to the 1981 data agrees with that of Maccagni *et al.* (1983). The data are consistent with an 8% ± 5% reduction in intensity between 1981 August and 1983 February.

The two *UBV* observations of 1981 September (Table 2) agree to within measuring errors. In 1983 January the source was ~0.16 mag (14%) fainter, but the color excesses give no evidence for spectral-shape variability. The *IUE* data are consistent with a similar intensity change. All the *UBV* data sets are best fitted by $\alpha = 1.30 \pm 0.14$, using the flux-density calibration of Johnson (1966). The infrared fluxes of 1983 January (Table 3) imply $\alpha = 0.7 \pm 0.4$.

Our six University of Michigan measurements at 14.5 GHz and four at 8 GHz, taken between 1983 January 1 and March 1, indicate no significant flux-density fluctuations, and data over this period have been averaged (Table 4). The 4.8 GHz flux density is affected by confusion with 3C 66B, only 6′ to the southeast (Northover 1973). All the single-antenna measurements contain emission from the resolved radio halo (≥ 10″) of 3C 66A (see Ulvestad, Johnston, and Weiler 1983). We have plotted the 4.9 and 15 GHz VLA and the 20.3 GHz OVRO flux-density values without correction in Figure 3, even though these contain some resolved emission. Our VLA observations indicated structure on scale sizes comparable to the synthesized beam sizes. There is thus no reason to assume that the falling spectrum, $\alpha = 0.3$, implied by the flux-density measure-

TABLE 4

RADIO OBSERVATIONS OF 3C 66A

	FLUX DENSITY (mJy)					
OBSERVATION	4.8 GHz	4.9 GHz	8 GHz	14.5 GHz	15 GHz	20.3 GHz
Single antenna, 1983 Jan–Mar	1780 ± 50	...	940 ± 20	720 ± 10	...	640 ± 20
VLA 1983 Feb	...	810 ± 50	...	...	580 ± 50	...
Single antenna, 1983 Dec	...	...	...	...	...	554 ± 9

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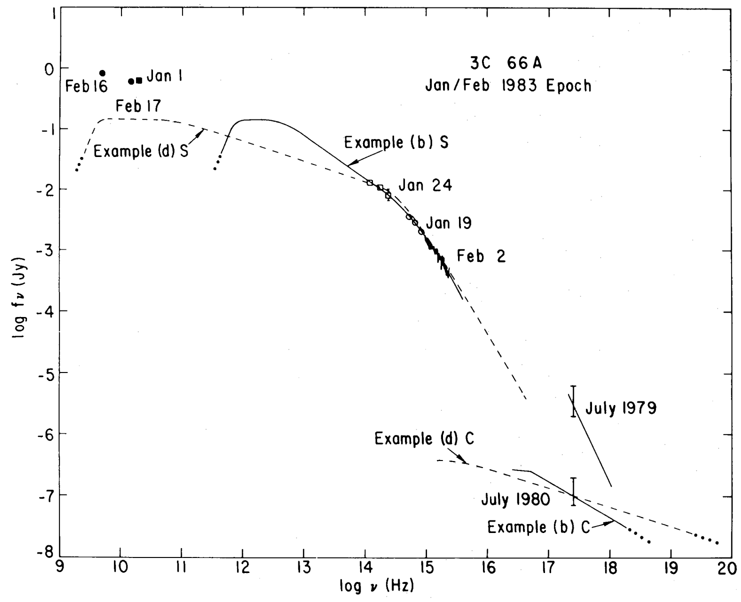

FIG. 3.—Flux densities of 3C 66A in 1983 January/February. The radio measurements are dominated by emission from resolved components, and we estimate that ~0.14 Jy is from the compact core. The earlier epoch X-ray measurements are from Maccagni, Maccacaro, and Tarenghi (1983) for 1979 July, and from Maccagni and Tarenghi (1981) for 1980 July. The synchrotron (S) and Compton (C) components produced by examples (b) and (d) in Table 5 are also shown.

ments at 4.9 and 15 GHz, is typical of the spectrum of the central core. Owen and Rudnick (1976) resolved components of 0″.4 ± 0″.1 (0.58 ± 0.04 Jy) and 0″.1 ± 0″.02 (0.59 ± 0.04 Jy) at 2.7 and 8.1 GHz, respectively, implying $\alpha \approx 0$. Our OVRO 20.3 GHz flux density is contaminated by halo emission, as mentioned above. However, Stannard, Edwards, and McIlwrath (1981) show the halo to exhibit a 5–20.3 GHz spectral index of ≥ 1.4. Assuming the halo flux density to be 0.36 Jy at 5 GHz (Weiler and Johnston 1980), the halo contribution at 20.3 GHz should be ≤ 0.05 Jy. The net 20.3 GHz radiation assumed to be from an angular size of $< 2''$ is thus 0.59–0.64 Jy, and the 5–20.3 GHz spectral index of this emission appears to be ≤ 0.0. The flux density that we are entitled to attribute to central core emission is, however, several times smaller still. Weiler and Johnston (1980), using VLBI in 1978, resolved a source of 1.5 mas, which, with any still unresolved emission, amounted to only 0.2 Jy at 15 GHz. Their 15 GHz measurement of radiation within an angular size of ~1″ was 0.52 Jy, similar to our value of 0.58 Jy. Therefore, we adopt 0.2 Jy as an *upper* limit to the central core ($\theta < 1.5$ mas) flux density for 1983 January/February. Our 20.3 GHz OVRO flux-density measurement of 1983 December was significantly lower than that of 1983 January (Table 4). Assuming that the source is not relativistically beamed, as argued later, variability over 11 months confirms the existence of a source smaller than 1.5 mas ($\theta \leq 0.2$ mas if $z = 0.05$, and $\theta \leq 0.02$ mas if $z = 0.44$; $H_0 = 40$ km s^{-1} Mpc^{-1}, $q_0 = 0$). We adopt the amount of the variability, 0.09 ± 0.02 Jy, as a *lower* limit to the central core emission for 1983 January/February. In our model fits in § IV*d*, we assume that 0.14 Jy is a reasonable estimate of the 1983 January/February flux density of the flat-spectrum core emission.

X-ray emission was detected from 3C 66A on four occasions with the 0.2–3 keV imaging proportional counter (IPC) of the *Einstein Observatory.* Maccagni and Tarenghi (1981) report a change of a factor of 15 in intensity between observations made a year apart. When the source was brightest, the *Einstein Observatory* monitor proportional counter (MPC) detected it between ~1.2 and 5 keV, simultaneously with the IPC, with $\alpha = 2.1 \pm 0.6$ (Maccagni, Maccacaro, and Tarenghi 1983). After an interval of only 4 days, the IPC intensity had dropped by ~30%, and the source was no longer detectable with the MPC. There is a suggestion from the IPC data that the spectral index steepened as the flux decreased. We see from Figure 3 that an extrapolation of our *IUE* spectrum would meet the 1980 July X-ray observation, but it falls short of the 1979 flux density.

IV. DISCUSSION

a) *BL Lac Object Spectral Curvature*

Spectral curvature in the infrared to ultraviolet region has been a property of all the BL Lac and related objects studied in our program, i.e., OJ 287 (Worrall *et al.* 1982; Maraschi *et al.* 1984), 3C 371 (Paper I), and OQ 530 and ON 325 (Paper II). We now add OI 90.4 and 3C 66A. We have selected these six sources for study because they are at relatively high galactic latitude, and galactic extinction, which could itself produce curvature similar to that observed, should be small or negligible. We must consider whether or not emission from host elliptical galaxies, similar to that detected spectroscopically or photometrically around a relatively large sample of BL Lac objects (Miller, French, and Hawley 1978; Weistrop *et al.* 1981 and references therein) can be the cause of the observed curvature. Of our six sources, 3C 371 is the only one for which there is a bright, well-studied galaxy, and in Paper I we found that subtracting its emission from our data gave resultant core emission that still showed strong curvature. Miller, French, and Hawley (1978) give a tentative redshift of 0.306 for OJ 287. Any such distant host galaxy (for which there is no observational evidence) would contribute significantly to the observed emission only if it were several times brighter than the brightest host galaxy so far observed. In Paper II we conclude that host galaxies are not the reason for the spectral curvatures in OQ 530 and ON 325. Our measurements of OI 90.4 show

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steepening between the *UBV* and the ultraviolet data. Such a steepening cannot be attributed to a standard elliptical galaxy, since its emission would cut off steeply between *B* and *U*. A galaxy subtraction would in fact tend to increase the amount of curvature. If 3C 66A is at a redshift of 0.444, or in a galaxy associated with the cluster along the line of sight at $z \approx 0.37$ (Butcher *et al.* 1976), we would expect the galaxy contribution to our observations of this source to be relatively small. The infrared to ultraviolet spectrum of 3C 66A is similar to that of ON 325, and if, instead, 3C 66A were near enough for the galaxy contribution to be significant, the curvature between infrared and *UBV* wavelengths could be removed only at the expense of producing curvature between the *UBV* and the ultraviolet. Concerning other BL Lac objects that have been observed in the ultraviolet, the review paper of Maraschi, Tanzi, and Treves (1983) lists PKS 2155−304 and PKS 0548−322 as showing spectral curvature. Five BL Lac objects are listed for which a single power law has been suggested to describe the data. The conclusions for these five may be weakened by the following: (1) the galactic emission to be subtracted is relatively bright in each case; (2) not all the objects have multifrequency spectra from a single epoch; and (3) further observations of one of them, Mrk 501, do suggest a spectral break (Kondo *et al.* 1981). We therefore tentatively conclude that infrared to ultraviolet curvature of BL Lac core radiation is at least a common, if not usual, property of BL Lac objects. We will define the characteristic frequency of the curvature as ν_{23}, to which physical interpretation is ascribed in § IV*d*. If ν_{23} varies, spectral changes will be measured in any given nearby frequency band. Spectral indices beyond the region of curvature may remain unchanged.

The source OI 90.4 is not the first BL Lac object for which *IUE* spectral variability has been reported. Small spectral variations are observed in PKS 2155−304; $\alpha \approx 0.7$–0.9 (Urry *et al.* 1982; Maraschi *et al.* 1983). Ulrich *et al.* (1984) report that Mrk 421 shows a larger range of spectral index, and, when it is brightest, intensity changes do not appear to be accompanied by spectral index changes, suggesting that ν_{23} has moved sufficiently far from the ultraviolet band. In one set of observations of OJ 287 the optical spectral index is an unbroken extension of the ultraviolet, whereas, when the source is brighter, the spectral index is flatter in the optical but unchanged in the ultraviolet (Maraschi *et al.* 1984). The data for this small sample of BL Lac objects imply that intensity changes and variations in ν_{23} may occur together, but in no obviously correlated manner.

b) OI 90.4

To compare our optical and infrared data for OI 90.4 with other published work, we first apply the same extinction corrections to all the spectra, assuming $A_v = 0.08$. The data of Puschell and Stein (1980), Rieke *et al.* (1977), and our work cover a range of ~1.4 in magnitude. However, the optical and infrared spectral indices are all consistent with values between about 1.0 and 1.2. The source undergoes *UBV* intensity variability as fast as one day (see § III*a* and Baumert 1980). It appears that ν_{23} does not usually lie in the optical band, but in the higher frequencies of the ultraviolet. Our *IUE* observations are the only strong indication of variability in ν_{23}.

c) 3C 66A

We have compared our optical and infrared observations with previous work by first correcting all to our assumed extinction of $A_v = 0.15$. Observations of O'Dell, Puschell, and Stein (1977) and Wills and Wills (1974) agree in spectral shape with our data. The intensity range is only ~0.25 mag, with our 1981 October observations being the brightest. Data of Tapia, Craine, and Johnson (1976) are, however, brighter still, by ~0.3 mag in *U*, but only ~0.1 mag in *V*. These observations fit our infrared spectral index of ~0.7, implying that ν_{23} has moved to a higher frequency. This is the only indication of a change in ν_{23}. The combined *HKL* and *UBVR* photometry of O'Dell, Puschell, and Stein (1977) are consistent with the same infrared to optical curvature as our observations. Optical variations over time scales of weeks to months have been observed in 3C 66A (Pica *et al.* 1980; Folsom *et al.* 1976).

d) SSC Emission Models for the BL Lac Objects

In Papers I and II, we applied two synchrotron self-Compton (SSC) emission models to the sources 3C 371, OQ 530, and ON 325. All these sources exhibit composite spectra similar to those presented here for OI 90.4 and 3C 66A. For the homogeneous SSC emission model with no electron reacceleration, the measured spectral curvature is assumed to be due to electron energy losses, and the synchrotron radiation is assumed to be self-absorbed at a frequency ≥100 GHz. A value of the Doppler factor, $\delta = (1 - \beta^2)^{1/2}/(1 - \beta \cos \theta)$, can be derived, where β is the bulk velocity in units of *c*, and θ is the angle of relativistic motion relative to the line of sight. Our previous work has found $\delta \geq 10$, 17, and 12 for 3C 371, OQ 530, and ON 325, respectively. To minimize δ we place OI 90.4 and 3C 66A at small redshift, $z = 0.05$, and assume that the maximum observed X-ray flux density is produced by Compton radiation. We then find $\delta \geq 60$ and 7, respectively, for these sources. The rather high values of δ that seem typical for this model may be a reason to consider it unlikely. We would expect geometry to provide some values of δ closer to 1.

An SSC model that includes electron reacceleration is presented by Königl (1981). We apply the model here to OI 90.4 and 3C 66A in a manner identical with the application to OQ 530 and ON 325 in Paper II. Table 5 corresponds to Table 3 of Paper II. The model describes a jet of path length *r* in which the magnetic field falls as r^{-m} and the electron density as r^{-n}, and in which electrons of spectral index $2\alpha_0 + 1$ are continuously reaccelerated. The observed radiation comes from a jet that extends from r_m (pc) to r_u (pc). A synchrotron spectrum is produced which exhibits the three spectral indices α_1, α_2, and α_3, with breaks at ν_{12} and ν_{23}. Radiation at ν_{12} comes predominantly from r_m, and radiation at ν_{23} comes predominantly from r_u. The parameters of the jet can be determined if the normalization of the synchrotron spectrum, these spectral parameters, the redshift, and the level of emission in Compton radiation are known. We can then find values for the required degree of relativistic beaming, the expected variability time scales and angular source sizes at various frequencies, and the low frequency, ν_1, at which the synchrotron spectrum is cut off by self-absorption.

In the sample fits presented in Table 5, we have assumed that $\alpha_1 = 0.0$, and that the flux density in this part of the spectrum is ~2 Jy for OI 90.4 and 0.14 Jy for 3C 66A. The infrared measurements constrain α_2 and, by spectral extrapolation, ν_{12}. The optical and ultraviolet data constrain ν_{23} and α_3. Our only X-ray measurements are from a different epoch, and we must make an assumption about the flux-density fraction, F_c/F_x, which is of Compton origin. For OI 90.4, we take the one measured flux density for F_x. For 3C 66A, we use the lower

TABLE 5

SSC Jet Model Fits

A. Input Parameters

Example	α_1	α_2	α_3	ν_{12} (GHz)	ν_{23} (GHz)	F_c/F_x	z
OI 90.4:							
(a)	0.0	1.1	1.6	1.5×10^3	1.0×10^6	1	0.05
(b)	0.0	1.0	1.6	8×10^2	1.0×10^6	1	0.05
3C 66A:							
(a)	0.0	0.7	1.6	4.5×10^3	4.0×10^5	1	0.05
(b)	0.0	0.7	1.6	4.5×10^3	4.0×10^5	1	0.44
(c)	0.0	0.35	1.6	5.0×10^1	4.0×10^5	0.1–1	0.05
(d)	0.0	0.35	1.6	5×10^1	4.0×10^5	1	0.44

B. Output Parameters

Example	α_0	m	n	δ	r_m (pc)	r_u (pc)	ν_1 (GHz)	$t_{\rm var}$ at ν_{12}	$t_{\rm var}$ at ν_{23}
OI 90.4:									
(a)	0.78	1.58	1.05	27	2.3×10^{-2}	2.4×10^{-1}	108	1 day	10 days
(b)	0.72	1.62	1.03	15	2.7×10^{-2}	3.2×10^{-1}	48	2 days	25 days
3C 66A:									
(a)	0.52	1.74	0.96	13.5	9.1×10^{-4}	3.7×10^{-3}	906	2 hr	7 hr
(b)	0.52	1.74	0.96	31	8.5×10^{-3}	3.4×10^{-2}	906	7.6 hr	1.3 days
(c)	0.27	1.98	0.81	1	$1\text{–}7 \times 10^{-2}$	$1\text{–}7 \times 10^{-1}$	3.2	13–90 days	4–28 mo
(d)	0.27	1.98	0.81	1.25	7.2×10^{-2}	7.1×10^{-1}	3.2	2 mo	1.8 yr

flux density of 1980 July. (The implications of an X-ray flux as large as that in 1979 July, with a steep spectrum, are discussed later in this section.) Our sample fits are for $F_c/F_x = 1$. At least OI 90.4 would appear to satisfy this condition, since the 1979 April X-ray measurement falls above an extrapolation of the 1979 March *IUE* data. A smaller F_c/F_x would produce a larger δ. Example (c) for 3C 66A finds that a value of $\delta = 1$ fits all values of $0.1 \leq F_c/F_x \leq 1$. We give fits for both sources at $z = 0.05$, and for 3C 66A at $z = 0.44$. The comparison of example (a) with (b), and (c) with (d), for 3C 66A, gives an indication of the effect of z on the solutions. We show selected examples in Figures 2 and 3.

Table 5 shows that the Königl (1981) jet model can describe both BL Lac objects. The source OI 90.4 shows similar characteristics to 3C 371 (Paper I) and OQ 530 (Paper II), in that δ is relatively large, 15–30, and the model only describes data at frequencies above ~ 50 GHz. Variability is of the order of days at ν_{23}, in rough agreement with the observations. Angel *et al.* (1978) report large changes in percentage polarization over a time scale of ~ 10 hr, which, if linked with intensity variability, may imply values of δ even larger than those given in Table 5. This object also shows a strong wavelength dependence in the polarization and an intermittent wavelength dependence in the position angle (Puschell *et al.* 1983; Bailey, Hough, and Axon 1983; Rieke *et al.* 1977). Since radiation at different wavelengths is emitted from different places in this jet model, these observations may be interpreted as indicating a positional dependence in magnetic field strength and direction. Examples (a) and (b) produce jets of only 0.006 and 0.01 mas, respectively, which must lie within the 0.6 mas component resolved by Weiler and Johnston (1980).

The source 3C 66A is similar to ON 325 (Paper II). Strong relativistic beaming is not required [examples (c) and (d)], and compact radio emission to frequencies as low as a few GeV may be produced. Examples (c) and (d) imply angular source sizes of >0.1 and ~ 0.04 mas, respectively, at ν_1. These sizes are similar to those implied by our observed 20.3 GHz variability, and are over 400 times as large as the values given by examples (a) and (b). The fastest variability so far observed at optical frequencies ($\sim \nu_{23}$) lies between the predictions for the first two and second two examples. This may suggest that the source does go through periods of moderate relativistic beaming. The polarization behavior of 3C 66A is in sharp contrast to that of OI 90.4. Angel *et al.* (1978) report it to have varied at most by $\pm 16°$ in position angle over 2 years and to have stayed constant in percentage polarization over a 40 day monitoring period.

None of the examples in Table 5 will give an X-ray spectrum steeper than $\alpha \approx 0.6$. The only good X-ray spectral measurement is for 3C 66A in 1979 July ($\alpha \approx 2$), when variability was measured on a faster time scale (4 days) than is usual at lower frequencies (see § III*b*). This X-ray emission could be accommodated if $F_c/F_x \ll 1$ at that time, and the X-ray emission were dominated by an extension of the synchrotron component. The X-ray emission would then be produced by the highest energy electrons, undergoing rapid energy loss at r_m, i.e., those electrons with the greatest demand for rapid reacceleration. Faster variability may thus be expected here, near the high-frequency cutoff, than in any other part of the synchrotron spectrum. Since the blue magnitude measured close in time to the 1979 July measurement (Pica *et al.* 1980) is similar to that plotted in Figure 3, the interpretation would have required a mean spectral index through the ultraviolet band of $\alpha \leq 1.1$ at that time, as pointed out by Maccagni *et al.* (1983). Monitoring of the X-ray and ultraviolet spectra of 3C 66A should yield interesting information.

V. SUMMARY

We summarize our results as follows:

1. The BL Lac objects OI 90.4 and 3C 66A both exhibit spectral curvature in the infrared to ultraviolet energy bands.

We infer this to be a usual property of the core radiation of BL Lac objects.

2. We have measured ultraviolet spectral-index variability in OI 90.4 over the time scale of 3 years. This is the first strong evidence of spectral-shape variability in the infrared to ultraviolet energy band for this source.

3. We have measured variability of 0.09 ± 0.02 Jy in the 20.3 GHz flux density of 3C 66A over the time scale of 11 months. Assuming that the source was not relativistically beamed during this time, this observation implies that the emission was from a source of angular size ≤ 0.2 mas ($z = 0.05$) or ≤ 0.02 mas ($z = 0.44$) ($H_0 = 50$ km s^{-1} Mpc^{-1}; $q_0 = 0$).

4. We have applied a synchrotron self-Compton jet model to each BL Lac object. We find that the OI 90.4 data are best satisfied by a jet with a relatively high degree of relativistic beaming, and emission at frequencies below ~50 GHz is not described by the model. We find that 3C 66A may not always undergo strong relativistic beaming, and the model may incorporate the small fraction of the total radio emission below ~20 GHz which is from within ~1.5 mas of the core.

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REFERENCES

Aller, H. D., Aller, M. F., and Hodge, P. E. 1981, *A.J.*, **86**, 325.
Angel, J. R. P., *et al.* 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 117.
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
Bailey, J., Hough, J. H., and Axon, D. J. 1983, *M.N.R.A.S.*, **203**, 339.
Baumert, J. H. 1980, *Pub. A.S.P.*, **92**, 156.
Birkinshaw, M., and Gull, S. F. 1984, *M.N.R.A.S.*, **206**, 359.
Boggess, A., *et al.* 1978, *Nature*, **275**, 372.
Bromage, G. E., Burton, W. M., Patchett, B. E., and Smith, A. G. 1980, *Proc. 2d European IUE Conf.* (ESA SP-157), p. 267.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Butcher, H. R., Oemler, A., Tapia, S., and Tarenghi, M. 1976, *Ap. J.* (*Letters*), **209**, L11.
Chiappetti, L., Maraschi, L., Tanzi, E. G., and Treves, A. 1982, *Proc. 3d European IUE Conf.* (ESA SP-176), p. 581.
Folsom, G. H., Miller, H. R., Wingert, D. W., and Williamon, R. M. 1976, *A.J.*, **81**, 145.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
Kondo, Y., *et al.* 1981, *Ap. J.*, **243**, 690.
Königl, A. 1981, *Ap. J.*, **243**, 700.
Maccagni, D., Maccacaro, T., and Tarenghi, M. 1983, *Ap. J.*, **273**, 70.
Maccagni, D., Maraschi, L., Tanzi, E. G., Tarenghi, M., and Chiappetti, L. 1983, *Ap. J.*, **273**, 75.
Maccagni, D., and Tarenghi, M. 1981, *Space Sci. Rev.*, **30**, 55.
Maraschi, L., Tanzi, E. G., Tarenghi, M., and Treves, A. 1983, *Astr. Ap.*, **125**, 117.
Maraschi, L., Tanzi, E. G., and Treves, A. 1983, *Mem. Soc. Astr. Italiana*, **54**, 399.
Maraschi, L., Tanzi, E. G., Treves, A., and Falomo, R. 1984, *Astr. Ap.*, in press.
Miller, J. S., French, H. B., and Hawley, S. A. 1978, in *Pittsburgh Conference on BL Lac Objects*, ed. A. M. Wolfe (Pittsburgh: University of Pittsburgh Press), p. 176.
Northover, K. J. E. 1973, *M.N.R.A.S.*, **165**, 369.
O'Dell, S. L., Puschell, J. J., and Stein, W. A. 1977, *Ap. J.*, **213**, 351.
Owen, F. N., and Rudnick, L. 1976, *Ap. J.*, **203**, 307.
Pica, A. J., Pollock, J. T., Smith, A. G., Leacock, R. J., Edwards, P. L., and Scott, R. L. 1980, *A.J.*, **85**, 1442.
Puschell, J. J., Jones, T. W., Phillips, A. C., Rudnick, L., Simpson, E., Sitko, M., Stein, W. A., and Moneti, A. 1983, *Ap. J.*, **265**, 625.
Puschell, J. J., and Stein, W. A. 1980, *Ap. J.*, **237**, 331.
Rieke, G. H., Lebofsky, M. J., Kemp, J. C., Coyne, G. V., and Tapia, S. 1977, *Ap. J.* (*Letters*), **218**, L37.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Schwartz, D. A., Madejski, G., and Ku, W. H.-M. 1982, in *IAU Symposium 97, Extragalactic Radio Sources*, ed. D. S. Heeschen and C. M. Wade (Dordrecht: Reidel), p. 383.
Stannard, D., Edwards, M. R., and McIlwrath, B. K. 1981, *M.N.R.A.S.*, **194**, 919.
Tapia, S., Craine, E. R., Gearhart, M. R., Pacht, E., and Kraus, J. 1977, *Ap. J.* (*Letters*), **215**, L71.
Tapia, S., Craine, E. R., and Johnson, K. 1976, *Ap. J.*, **203**, 291.
Ulrich, M. H., Hackney, K. R. H., Hackney, R. L., and Kondo, Y. 1984, *Ap. J.*, **276**, 466.
Ulvestad, J. S., Johnston, K. J., and Weiler, K. W. 1983, *Ap. J.*, **266**, 18.
Urry, M., Holt, S., Kondo, Y., and Mushotzky, R. 1982, in *Advances in Ultraviolet Astronomy*, ed. Y. Kondo, J. M. Mead, and R. D. Chapman (NASA Pub. 2238; Washington: Government Printing Office), p. 177.
Weiler, K. W., and Johnston, K. J. 1980, *M.N.R.A.S.*, **190**, 269.
Weistrop, D., Shaffer, D. B., Mushotzky, R. F., Reitsema, H. J., and Smith, B. A. 1981, *Ap. J.*, **249**, 3.
Wills, B. J., and Wills, D. 1974, *Ap. J.* (*Letters*), **190**, L97.
Worrall, D. M. *et al.* 1982, *Ap. J.*, **261**, 403.
Worrall, D. M., *et al.* 1984*a*, *Ap. J.*, **278**, 521 (Paper I).
Worrall, D. M., *et al.* 1984*b*, *Ap. J.*, **284**, 512 (Paper II).

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