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THE ULTRAVIOLET TO INFRARED ENERGY DISTRIBUTION OF THE BL LACERTAE OBJECT PKS 0422+00 AT TWO DIFFERENT BRIGHTNESS LEVELS[1]

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ABSTRACT

The BL Lacertae object PKS 0422+00 was observed with *IUE* (*International Ultraviolet Explorer*) on 1987 August 31–September 1, when the visual magnitude of the object was $V = 16.2$, and again ~4 months later (1988 Jan 10) during an active state ($V = 15.6$). Quasi-simultaneous optical to infrared observations allow deriving a detailed spectral flux distribution from 8×10^{13} to 2.5×10^{15} Hz, for each epoch. Fits in terms of broken power laws and logarithmic parabolas are discussed.

Subject headings: BL Lacertae objects — galaxies: individual (PKS 0422+00) — spectrophotometry

I. INTRODUCTION

The strongly variable radio source PKS 0422+00 was identified by Bolton, Shimmins, and Merkelijn (1968) with a star-like counterpart ($m_v \approx 17$), whose featureless optical spectrum (Wills and Wills 1976) and variable optical polarization (Angel *et al.* 1978) revealed its BL Lacertae nature. The source, being a strong millimeter emitter (Owen *et al.* 1978), was selected by Owen, Helfand, and Sprangler (1981) for observations with the *Einstein Observatory* and exhibited a comparatively high X-ray emission. Far-IR measurements with *IRAS* are reported by Impey and Neugebauer (1988).

Optical monitoring by Pica *et al.* (1980) and by Moles *et al.* (1985) showed erratic variability in the range $V \approx 15.5$ to $V \approx 16.5$, with occasional dips down to $V \approx 17.4$. An optical flare of 8 days duration (from $V \approx 15.8$ to $V \approx 14.8$) was observed in 1984 by Worrall *et al.* (1986) with changes of spectral slope of $\Delta\alpha \simeq 0.7$ which do not correlate with flux. Similar variations of both flux and spectral slope were observed in 1983 by Moles *et al.* (1985). A variation $\Delta B \simeq 0.6$ in 20 hr was recorded by Xie Guang Zhang *et al.* (1988). Lesser variability ($\Delta m \simeq 1.5$) was detected in the near-IR (Allen, Ward, and Hyland 1982; Holmes *et al.* 1984; Lepine, Braz, and Epchtein 1985; Sitko *et al.* 1983), all measurements being consistent with a constant spectral slope $\alpha_{IR} \simeq 1.1$.

As part of our current study of the spectral flux distribution of blazars, PKS 0422+00 was being monitored at optical frequencies since 1986 September. The object was at intermediate brightness, declining slowly from $V = 15.5$ on 1986 September to $V = 16.2$ in 1987 August, when the first *IUE* observations could be obtained, together with quasi-simultaneous optical observations. In 1988 January, when the object regained a brightness $V \simeq 15.6$, new UV observations, complemented by simultaneous optical to IR spectrophotometry, were obtained. These observations, together with previous optical to IR spectrophotometry, allow a detailed study of the spectral flux distribution from 8×10^{13} Hz to 2.5×10^{15} Hz at two different brightness states. A preliminary account of these observations was given in Falomo *et al.* (1988*a*) and Tanzi *et al.* (1988).

II. OBSERVATIONS AND DATA ANALYSIS

The *IUE* observations of PKS 0422+00 were obtained on 1987 August 31 and on 1988 January 10 with the Short Wavelength Primary camera (SWP; range: 1200–1950 Å), and on 1987 September 1 with the Long Wavelength Primary camera (LWP; range: 2000–3200 Å). A journal of observation is given in Table 1. The source was acquired in the large aperture (10″ × 20″ oval) of the spectrograph by means of the blind offset procedure with coordinates $\alpha(1950) = 04^h22^m13^s.00 \pm 0^s.03$ and $\delta(1950) = +00°29'17''.1 \pm 0''.5$ as measured on a paper copy of the blue POSS. The line-by-line–extracted spectra, as derived from the standard IUESIP code, were carefully examined for the presence of flaws and cosmic-ray events. Several spectral regions were discarded because of the presence of substantial flaws either in the spectrum itself or in the adjacent background. Fluxes in reliable spectral intervals are reported in Table 2 in absolute units, using the calibration curves by Bohlin and Holm (1980) and Cassatella and Harris (1983). The final reduction was accomplished adopting an extraction slit seven scan lines long, corresponding to 3 times the full width at half-intensity of the Gaussian fitting to the transverse profile of the line-by-line–extracted spectrum.

No emission or absorption line was detected over the faint continuum, which appears well represented by a single power

[1] Based on UV observations with the *International Ultraviolet Explorer* collected at the European Space Agency Tracking Station in Villafranca (Spain). Optical and IR observations were obtained at the European Southern Observatory, La Silla (Chile) and at the Asiago Observatory, Asiago (Italy).

TABLE 1

Journal of Observations

Date (UT)	Instrument	Range	Magnitude or Flux (10^{-16} ergs cm^2 s^{-1} Å^{-1})	Spectral Index (α_ν)
1986 Sept 11.1	ESO 1.5 m + B & C + IDS	4000–8000 Å	$V = 15.5 \pm 0.08$[a]	1.87 ± 0.03[b]
1986 Dec. 4.2	Asiago 1.82 + CCD	*V*, *R*	$V = 16.0 \pm 0.05$	1.72 ± 0.05
1987 Jan 9.1	ESO 1.5 m + B & C + IDS	3800–7800 Å	$V = 16.0 \pm 0.06$	1.72 ± 0.05
	ESO 3.60 m + InSb + phot	*J*, *H*, *K*, *L*	$F(2.18\ \mu m) = 9.05 \pm 0.1$	1.20 ± 0.17
1987 Aug 30.8	ESO 1.5 m + B & C + CCD	4000–7300 Å	$V = 16.2 \pm 0.1$	1.80 ± 0.02
1987 Aug 31.8	*IUE* + LWP	2000–3200 Å	$F(2500\ Å) = 15.0 \pm 0.17$	3.70 ± 0.80
1987 Sep 1.8	*IUE* + SWP	1200–1950 Å	$F(1500\ Å) = 14.7 \pm 2.1$	1.79 ± 0.23
1987 Dec 23	Asiago 1.82 + CCD	*B*, *V*, *R*, *I*	$V = 15.8 \pm 0.1$	1.80 ± 0.25
1988 Jan 9.1	ESO 1.5 m + B & C + CCD	4000–7300 Å	$V = 15.6 \pm 01$	1.74 ± 0.02
	ESO-MPI 2.2 m + InSb phot	*J*, *H*, *K*, *L*	$F(2.18\ \mu m) = 10.1 \pm 0.3$	1.22 ± 0.08
1988 Jan 10.1	ESO 1.5 m + B & C + CCD	4000–7300 Å	$V = 15.55 \pm 0.06$	1.73 ± 0.01
	ESO-MPI 2.2 m + InSb phot	*J*, *H*, *K*, *L*	$F(2.18\ \mu m) = 10.0 \pm 0.2$	1.08 ± 0.13
1988 Jan 10.5	*IUE* + SWP	1200–1950 Å	$F(1500\ Å) = 25.8 \pm 1.8$	1.84 ± 0.13
1988 Jan 11.1	ESO 1.5 m + B & C + CCD	4000–7300 Å	$V = 15.55 \pm 0.06$	1.69 ± 0.02
	ESO-MPI 2.2 m + InSb phot	*J*, *H*, *K*, *L*	$F(2.18\ \mu m) = 11.2 \pm 0.1$	1.17 ± 0.09
1988 Jan 12.1	ESO 1.5 m + B & C + CCD	6000–9500 Å	...[c]	1.69 ± 0.04

[a] 1 σ statistical uncertainty.
[b] 90% confidence level.
[c] No photometrically corrected data are available (see text).

law. The best fit to the combined SWP+LWP data of 1987 yields $\alpha = 2.30 \pm 0.13$ (the 90% confidence level is quoted for spectral indexes throughout the paper, where $F_\nu \propto \nu^{-\alpha}$).

No direct indication of extinction is found in the UV spectra; however, the sensitivity of the LWP camera is poor around 2200 Å. Using the hydrogen column density in the direction of the source (Stark *et al.* 1989) and assuming the mean galactic gas-to-dust ratio (Savage and Mathis 1979) one gets $A_V = 0.27$ which, however, appears to overcorrect the UV data in the sense that the energy distribution would flatten substantially at high frequencies. Therefore no reddening correction was applied to the data.

TABLE 2

Ultraviolet Fluxes in Selected Bands[a]

$\Delta\lambda$	F_λ	r.m.s.[b]
SWP 31687 (exposure 21,780 s)		
1238–1270........................	1.33	0.23
1290–1368........................	1.55	0.19
1384–1450........................	1.30	0.18
1515–1575........................	1.47	0.21
... .	...	...
1800–1890........................	1.31	0.07
... .	...	...
SWP 32697 (exposure 24,000 s)		
1250–1280........................	2.83	0.32
... .	...	...
1340–1430........................	2.68	0.15
1450–1550........................	2.58	0.18
1650–1750........................	2.45	0.11
1750–1850........................	2.70	0.13
1850–1950........................	2.55	0.08
LWP 11538 (exposure 9000 s)		
2440–2520........................	1.50	0.17
2560–2650........................	1.42	0.10
2670–2770........................	1.62	0.13
2800–2900........................	1.55	0.05

[a] Units: 10^{-15} ergs cm^2 s^{-1} Å^{-1}.
[b] 1 σ statistical uncertainty.

Optical spectrophotometry was obtained with the Boller and Chivens (BC) spectrograph at the ESO 1.5 m telescope (La Silla, Chile) at different epochs (see Table 1). The Image Dissector Scanner (IDS) was used to record the spectra of 1986 September 11 and 1987 January 9, while for spectra obtained after 1987 August 29, a CCD detector (RCA SID 503) was used. A dispersion of 224 Å mm^{-1} yielding a resolution of 18 Å (FWHM) for the IDS and of 12 Å for the CCD was adopted. In order to obtain photometrically corrected data an 8″ slit was used; from repeated observations of standard stars (Stone 1977) during each night, a photometric accuracy better than 10% is derived for all observations except that of 1988 January 12 which, due to poor sky conditions, may be uncertain by up to 50%. Photometry in the Cousins system was obtained on 1986 December 4 (*V* and *R* filters) and on 1987 December 23 (*B*, *V*, *R*, *I* filters) with the CCD camera (Bortoletto and D'Alessandro 1986) at the 1.82 m Asiago Observatory telescope.

Magnitudes and spectral slopes obtained for each night are reported in Table 1. *V* magnitudes were derived from spectrophotometric data by converting the monochromatic fluxes at 5500 Å according to the absolute calibration given by Bessel (1979). Spectral indexes are computed by single power-law fitting to the data; the uncertainty quoted corresponds to 90% confidence.

Infrared photometry in *J* (1.24 μm), *H* (1.63 μm), *K* (2.18 μm), and *L* (3.78 μm) was obtained with an InSb photometer attached to the ESO 3.6 m telescope (1987 Jan 9) and the ESO-MPI 2.2 m telescope (1988 Jan 9–11). In Table 3 the observed magnitudes and colors, together with the 1 σ statistical uncertainty are reported. A 15″ circular aperture, with chopper throw of 20″ in the east-west direction, was used. Several standard stars were repeatedly observed during each night in order to check photometric accuracy. Conversion to flux density was performed using the zero-magnitude fluxes given in Falomo *et al.* 1988*b*). In Table 1 the monochromatic flux at 2.18 μm observed each night is reported, together with the 1 σ statistical uncertainty; the spectral index of the best-fitting power law is also given for each observation.

TABLE 3

INFRARED MAGNITUDES OF PKS 0422+00

Date (UT)	K	$J-H$	$H-K$	$K-L$
1987 Jan 9.1	11.67	0.94	0.92	1.57
	0.02[a]	0.03	0.03	0.09
1988 Jan 9.1	11.55	0.88	0.87	1.77
	0.03	0.04	0.04	0.12
1988 10.1	11.56	0.87	0.86	1.57
	0.02	0.04	0.04	0.14
1988 11.1	11.43	0.87	0.90	1.67
	0.01	0.02	0.02	0.10

[a] 1 σ statistical uncertainty.

IV. DISCUSSION

From the observations of 1988 January 10, obtained within few hours (see Table 1), the spectral flux distribution of the source from 8×10^{13} to 2.5×10^{15} Hz, strictly pertaining to the same brightness state, can be derived (upper tracings of Fig. 1). For the lower intensity state of 1987 August 31–September 1, the UV and optical observations were obtained within 2 days, but no quasi-simultaneous IR data were taken. However, since the results of the optical observations coincide, in flux level and spectral slope, with those of 1987 January when IR data were also obtained (see Table 1), we can construct a composite spectral flux distribution from 8×10^{13} to 2.5×10^{15} Hz, taking advantage of the fact that IR and UV observations, although taken 8 months apart, refer to the same optical brightness level and spectral slope. This procedure, however, should be taken with caution since the constancy of the emission in the visible range does not imply equality at other frequencies.

The spectral flux ratio between the two states is clearly different at different frequencies, being of a factor of 2.0 in the far-UV, 1.7 in the visible range, and 1.1–1.2 in the infrared. In both the high and low state, the spectrophotometric data in the visible range are well fitted by single power laws with, respectively, $\alpha = 1.73 \pm 0.01$ and $\alpha = 1.80 \pm 0.02$. In the high state the same spectral slope holds up to 9500 Å, as shown by the observations of 1988 January 12 when scaled to match the January 11 data in the overlapping spectral range (see Table 1 and Fig. 1). The extrapolation toward the infrared of the power-law fits to the optical data accounts also for the J band data in both states, while at lower frequencies (H, K, and L bands), a marked flattening is apparent ($\alpha = 1.01 \pm 0.02$ and $\alpha = 0.96 \pm 0.10$ in the high and low state, respectively). An abrupt change in spectral shape ($\Delta\alpha = 0.7$–0.8) is thus occurring grossly around 2×10^{14} Hz in both states.

In the UV, the intermediate-frequency data (LWP camera) appear to be in excess over a smooth interpolation between optical and far-UV data. A similar effect was observed for PKS 0048−09 (Falomo *et al.* 1986*b*). We suspect that this could be due to inadequacies of the adopted response curve at low flux levels (see, e.g., Gondhalekar and Ferland 1987; George 1988). Connecting the far-UV data to the high-frequency end of the visible spectrum with a single power-law fit yields $\alpha = 2.08 \pm 0.05$. A slightly different slope $\alpha = 1.94 \pm 0.02$ is found with the same procedure for the high state. A further steepening $\Delta\alpha \simeq 0.2$–0.3 is thus apparent between optical and UV frequencies in both brightness states. Whether this is real

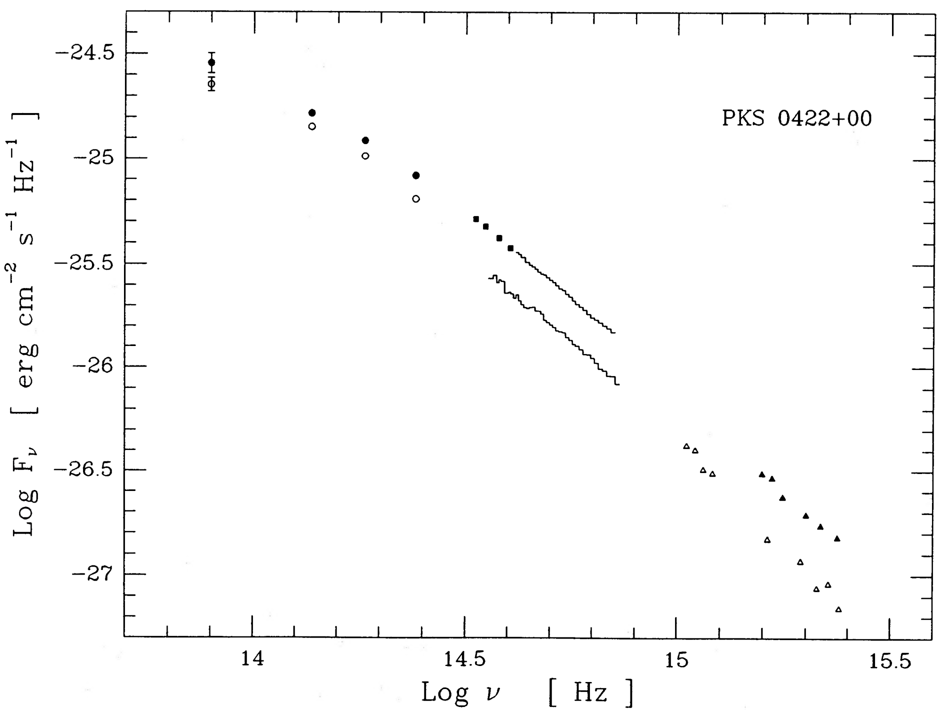

FIG. 1.—The UV to near-infrared energy distribution of PKS 0422+00 as derived from coordinated observations of 1988 January 10 and quasi-simultaneous observations of 1987 January 9 (optical-IR) and 1987 August (optical-UV). Filled circles show observations of 1988 January 10.1 UT; filled squares, observations of 1988 January 12.1 UT. The upper steplike line is the mean of 1988 January 9–1. Filled triangles show observations of 1988 January 10.5 UT (SWP 32697); open circles, observations of 1987 January 9.1 UT. The lower steplike line is the mean of 1987 January 9.1 and August 30.8 UT. The open tangles show observations of 1987 August 31.8 UT (LWP 11538) and of 1987 September 1.8 UT (SWP 31687).

or, at least in part, attributable to interstellar extinction suffered by the source is difficult to assess. In view of this uncertainty we choose to fit a single power law to the entire visible to far-UV range, to be compared with single power-law fits of the $L(8 \times 10^{13})$ to $H(2 \times 10^{14})$ broad-band data. The result is shown in Figure 2*a* together with the relevant parameters of the fits (see figure legend).

The data can be also fitted by logarithmic parabolas as proposed by Landau *et al.* (1986), which exhibit a continuous steepening for increasing frequencies. This type of curve was shown to be a global description of the radio to UV energy distribution of a large sample of blazars. Parabolic fits to our infrared to UV data were attempted for both brightness states. The fits give $\chi^2_{\rm red}$ comparable to those for the broken power laws (see Fig. 2*b*). As the fits are restrained to only one decade in frequency, a direct comparison with the average properties of blazars, in terms of the parameterization reported by Landau *et al.* (1986), is of little significance.

Both types of fit extrapolated to the X-ray band yield a flux which is a factor ~50 lower than that detected by the *Einstein Observatory*. The X-rays could represent an independent component, possibly attributable to synchrotron self-Compton processes. However, due to the large variability of the source, the possibility that the X-ray observation correspond to a particularly active state of the source cannot be excluded.

The shape of the quiescent infrared to UV distribution of PKS 0422+00 in either state appears to conform to the average behavior derived by Ghisellini *et al.* (1986) for a sample of 30 blazars. Its dynamical behavior, however, differs remarkably from that observed in other objects of the class (see, e.g., Bregman, Maraschi, and Urry 1987). We refer here in particular to PKS 0048−09 and PKS 0537−44, among the few blazars observed in some detail. In PKS 0048−09 the IR to UV spectrum is accounted for by a single power law, which hardens by $\Delta\alpha = 0.5$ for a $\Delta V \simeq 1.2$ brightening (Falomo *et al.* 1988*b*). In PKS 0537−44 the same single power law is found to hold in the IR–optical range over a variation of 2 mag (Tanzi *et al.* 1986; Falomo *et al.* 1988*c*). PKS 0422+00 exhibits a more complex behavior with varying intensity, with a possible hardening of the *break* frequency at higher intensity.

These differences could result from a finer spectral coverage obtained for this source or represent a behavior really intermediate between those of PKS 0048−09 and PKS 0537−44. We note also that some of the differences in the spectral flux distributions and variability regimes at different frequencies could arise from different (in the frame of the objects) observed spectral regions. In fact the redshift of PKS 0537−44 ($z = 0.898$) is relatively high with respect to the average of the class (see, e.g., Véron-Cetty and Véron 1987), while for the other two objects the redshift is yet unknown.

Before drawing any conclusions, a detailed series of observations of this object (as well as of others known to exhibit comparable variability regimes) are needed in order to describe the time evolution of the IR-to-UV spectrum. In fact, dealing just with sparse snapshots could induce an excessively fragmented classification of the observed behavior, thus obscuring any underlying unified scenario. Due to an increasing appreciation of the importance of multifrequency monitoring of such objects with suitable simultaneity and time coverage, systematic data should become available rather soon.

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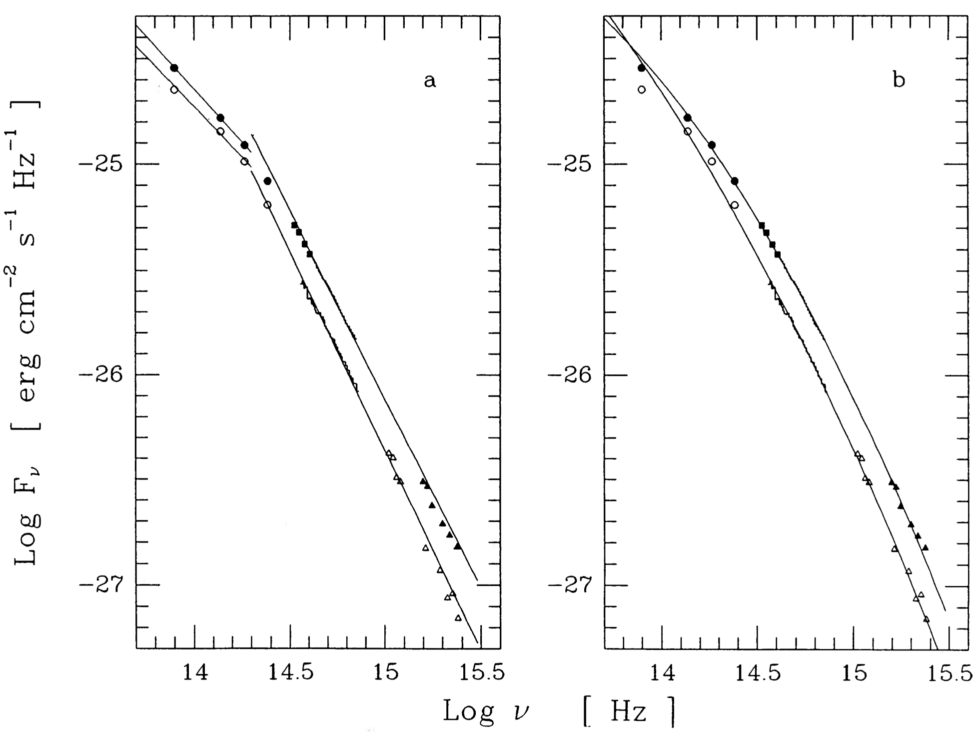

FIG. 2.—Broken power laws (*a*) and logarithmic parabolas (*b*) are fitted to the IR to UV energy distribution of PKS 0422+00 in the two brightness states observed. The relevant parameters of the fits are as follows. Broken power laws: high state $\alpha_{\rm IR} = 1.01 \pm 0.02$ ($\chi^2_{\rm red} = 0.02$), $\alpha_{\rm OPT-UV} = 1.82 \pm 0.02$ ($\chi^2_{\rm red} = 4.5$); low state $\alpha_{\rm IR} = 0.96 \pm 0.01$ ($\chi^2_{\rm red} = 1.3$), $\alpha_{\rm OPT-UV} = 1.90 \pm 0.09$ ($\chi^2_{\rm red} = 1.1$). Logarithmic parabolas: high state $\chi^2_{\rm red} = 01.3$, low state $\chi^2_{\rm red} = 2.5$.

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