

QUASI-SIMULTANEOUS ULTRAVIOLET OPTICAL AND INFRARED OBSERVATIONS OF THE BL LACERTAE OBJECT PKS 0048–09¹

R. FALOMO,² P. BOUCHET,³ L. MARASCHI,⁴ E. G. TANZI,⁵ AND A. TREVES⁴

Received 1987 October 19; accepted 1988 May 24

ABSTRACT

The first *International Ultraviolet Explorer* (IUE) observations of the BL Lacertae object PKS 0048–09 were obtained on 1987 January 7 and 8, when the object was in a moderately high optical state ($m_v \approx 15.5$ mag). Quasi-simultaneous optical-IR spectrophotometry allows deriving the detailed energy distribution from $\sim 10^{14}$ to $\sim 2.5 \times 10^{15}$ Hz. Comparison with previous published data, pertaining to a lower state of the source, indicates spectral hardening with increasing intensity on time scales of months.

Subject headings: BL Lacertae objects — galaxies: individual (PKS 0048–09) — spectrophotometry — ultraviolet: spectra

I. INTRODUCTION

PKS 0048–09 is a lineless BL Lac object which exhibits violent optical variability with $\Delta V \sim 3$ mag. (Usher, Kolpanen, and Pollock 1974). Variations of ~ 1 mag in 10 days have been observed (Barbieri *et al.* 1983; Pica and Smith 1983; Adam 1985). Also in the near-infrared, large amplitude variations on short time scales were monitored (Glass 1981; Allen, Ward, and Hyland 1982; Brindle *et al.* 1986). Strong variable optical polarization was measured by Kinnin (1984). The object is a well-known variable flat spectrum radio source (see, e.g., Wardle, Moore, and Angel 1984 and references therein). It has been detected in the X-ray with the *Einstein Observatory* (Madejski and Schwartz 1983).

In the course of our multifrequency monitoring program of active galactic nuclei (AGNs) PKS 0048–09 was observed in the optical range on 1986 September 12 at an intermediate brightness level ($V \approx 16.7$ mag). In early 1986 December a brighter state ($\Delta m \sim 2$ mag) was found. A month later, with the object at $V \approx 15.5$, well within the reach of the *International Ultraviolet Explorer* (IUE), the first UV observation of the object was secured (Falomo *et al.* 1987). Quasi-simultaneous visible-IR spectrophotometry allowed to derive a detailed energy distribution from $\sim 10^{14}$ to $\sim 2.5 \times 10^{15}$ Hz pertaining to a moderately high state of the source.

II. OBSERVATIONS

The IUE observations of PKS 0048–09 (see Table 1) were obtained on 1987 January 7.5 UT in the Short Wavelength Primary camera (SWP; range: 1200–2000 Å) with exposure time of 258 minutes, and on January 8.5 UT in the Long Wavelength Primary camera (LWP; range: 2000–3200 Å) with exposure time of 154 minutes. The source was acquired in the large aperture ($10'' \times 20''$ oval) of the spectrograph by means of the blind off-set procedure with coordinates $\alpha(1950) = 00^h48^m09^s.95$ and $\delta(1950) = -09^\circ45'24''.1$ 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 particles events. The final reduction was accomplished adopting an extraction slit whose length of seven scan lines corresponds to three times the full width at half-intensity of the Gaussian fitting to the transverse profile of the line by line extracted spectrum. The adopted slit length, while slightly reducing the total intensity ($\lesssim 2\%$), substantially improves the overall S/N ratio with respect to the standard slit length (11 scan lines). The combined (SWP + LWP) extracted spectrum, reduced to absolute flux by means of the calibration curves given in Bohlin and Holm (1980) and Cassatella and Harris (1983) is shown in Figure 1. No emission or absorption line can be recognized. The continuum appears well represented by a single power law (see Fig. 1). The best fit to the data, rebinned in 100 Å bins, rejecting regions heavily affected by spurious effects, yields $\alpha_v = 1.39 \pm 0.03$ (90% confidence level); the spectral indexes of each separate wavelength range are given in Table 1.

The counting rates of the Fine Error Sensor (FES) aboard IUE were recorded just before exposing the SWP camera on January 7.4 and immediately after exposing the LWP camera on January 8.6. Conversion to visual magnitudes (as given in Falomo *et al.* 1987) is however affected by large uncertainties (see Table 1) in both occasions, due to the possible higher than normal background light contribution by the Earth airglow during observations.

Optical spectrophotometry in the range 4000–8000 Å was obtained at the ESO 1.5 m telescope at La Silla (Chile) on 1986 September 12.1 and 1987 January 8.1 and 9.1 UT. The Boller & Chivens (BC) spectrograph at a dispersion of 224 Å mm^{-1} and the Image Dissector Scanner (IDS) were used with a $8'' \times 8''$ slit, at a resulting resolution of 18 Å (FWHM). Repeated observations of standard spectrophotometric stars (Stone 1977) yielded an average photometric accuracy of $\pm 5\%$ (1σ). Photometry in the V and B Johnson filters was obtained on 1986 December 5 with the CCD camera (Bortoletto and D'Alessandro 1986) at the 1.82 m Asiago Observatory telescope and in the V filter on 1987 January 6 with the photoelectric photometer at the 1 m ESO telescope at La Silla. A complete journal of the observations is given in Table 1 together with magnitudes and spectral slopes derived for each night. The V magnitudes were derived from IDS spectra con-

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).

² Osservatorio Astronomico di Padova, Italy.

³ European Southern Observatory, La Silla, Chile.

⁴ Dipartimento di Fisica, Università di Milano, Italy.

⁵ Istituto di Fisica Cosmica, CNR, Milano, Italy.

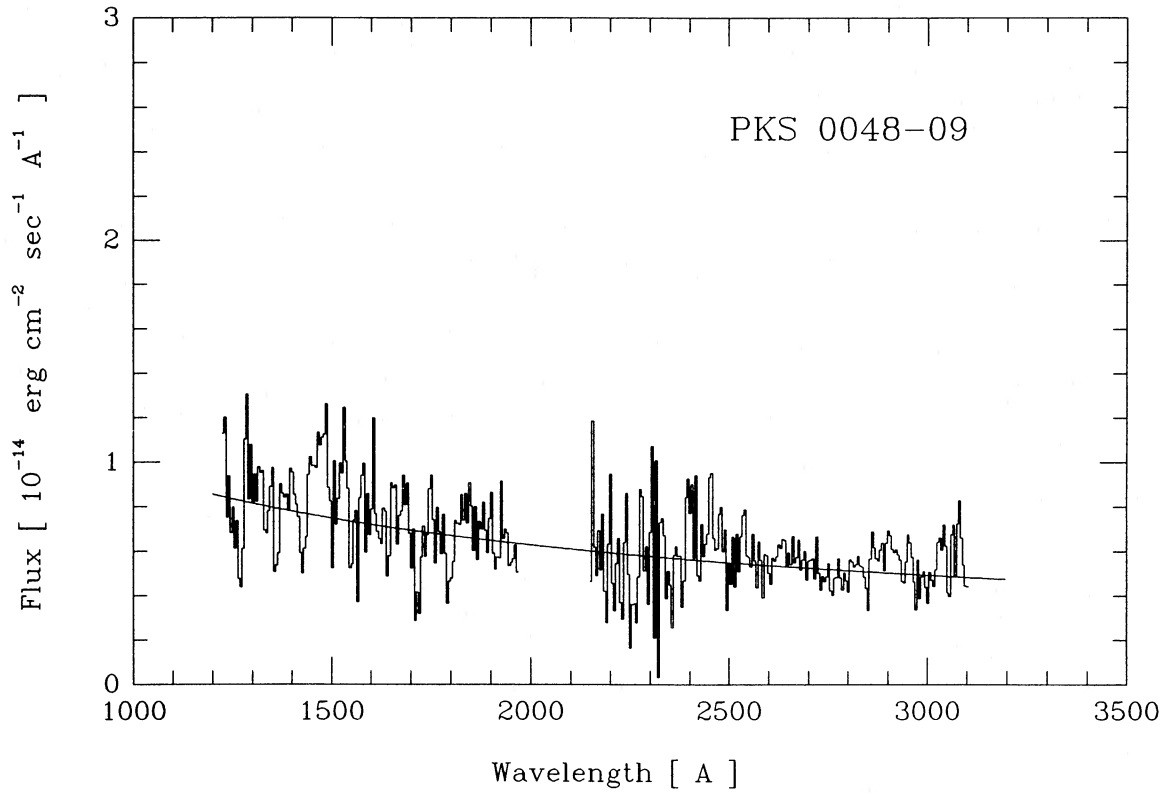


FIG. 1.—Combined (SWP 30039 and LWP 9886) spectrum (rebinned at 5 Å) of PKS 0048–09 in a moderately high brightness state (1987 January 7 and 8). Data in the 1950–2150 Å range, being affected by substantial flaws, are omitted. The best-fitting power law ($\alpha_\lambda = 0.061 \pm 0.03$) is superposed onto the data.

TABLE 1
JOURNAL OF OBSERVATIONS

Date	(UT)	Instrument	Range ^a	Magnitude or Flux ^b	Spectral Index
1986 Sep	12.1....	ESO 1.5 m + B&C + IDS	4000–8000 Å	$V = 16.7 \pm 0.08^c$	$\alpha_v = 1.47 \pm 0.02^d$
Dec	4.9....	Asiago 1.82 + CCD	B, V	$V = 14.9 \pm 0.1$	$B - V = 0.5$
1982 Jan	6.0....	ESO 1.0 m + photometer	V	$V = 15.2 \pm 0.2$	...
1987 Jan	7.4....	IUE + FES	...	$V = 14.5 \pm 0.7$	...
1987 Jan	7.5....	IUE + SWP	1230–1960 Å	$F(1500 \text{ Å}) = 83 \pm 3$	$\alpha_v = 1.3 \pm 0.1$
1987 Jan	8.1....	ESO 1.5 m + B&C + IDS	3800–7800 Å	$V = 15.5 \pm 0.06$	$\alpha_v = 0.96 \pm 0.05$
		ESO 3.6 m + InSb photometer	$\lambda_{\text{eff}} = 1.24 \mu\text{m}$	$F_\lambda = 11.4 \pm 0.07$	...
			$\lambda_{\text{eff}} = 1.63 \mu\text{m}$	$F_\lambda = 8.95 \pm 0.2$	...
			$\lambda_{\text{eff}} = 2.18 \mu\text{m}$	$F_\lambda = 6.16 \pm 0.1$	...
1987 Jan	8.5....	IUE + LWP	2200–3100 Å	$F(2500 \text{ Å}) = 55 \pm 2$	$\alpha_v = 1.7 \pm 0.05$
1987 Jan	8.6....	IUE + FES	...	$V = 14.7 \pm 0.7$	...
1987 Jan	9.1....	ESO 1.5 m + B&C + IDS	3800–800 Å	$V = 15.6 \pm 0.06$	$\alpha_v = 0.96 \pm 0.05$
		ESO 3.0 m + InSb photometer	$\lambda_{\text{eff}} = 1.24 \mu\text{m}$	$F_\lambda = 11.4 \pm 0.05$	...
			$\lambda_{\text{eff}} = 1.63 \mu\text{m}$	$F_\lambda = 8.95 \pm 0.2$	...
			$\lambda_{\text{eff}} = 2.18 \mu\text{m}$	$F_\lambda = 6.16 \pm 0.1$	...
			$\lambda_{\text{eff}} = 3.78 \mu\text{m}$	$F_\lambda = 3.78 \pm 0.6$	...
		ESO 3.6 m + CVF	1.5–2.5 μm	$F(2.2 \mu\text{m}) = 5.5$	$\alpha_v = 0.85 \pm 0.10$

^a Effective range.

^b In units of $10^{-16} \text{ ergs cm}^2 \text{ s}^{-1} \text{ Å}^{-1}$.

^c 1σ statistical uncertainty.

^d 90% confidence level.

verting the monochromatic fluxes at 5500 Å according to the absolute calibration given by Bessel (1979). Spectral indexes are computed by a single power-law fitting to the data; the uncertainty quoted corresponds to the 90% confidence level.

Infrared photometry in the $J(\lambda_{\text{eff}} = 1.24 \mu\text{m})$, $H(\lambda_{\text{eff}} = 1.63 \mu\text{m})$, $K(\lambda_{\text{eff}} = 2.18 \mu\text{m})$, and $L(\lambda_{\text{eff}} = 3.78 \mu\text{m})$ was obtained on 1987 January 8.1 and 9.1 UT with the InSb photometer at the ESO 3.6 m telescope at La Silla. A 15" circular aperture with chopper throw of 20" in the east-west direction was used. Infrared spectrophotometry, in the range 1.5–2.5 μm , was also obtained on January 9.1 UT with a Circular Variable Filter (CVF) at a resolution of ~ 60 Å. Several standard stars were repeatedly observed during each night in order to check photometric accuracy. Conversion to flux density was performed with the following zero-magnitude fluxes (units of $\text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$): $F(J=0) = 3.24 \times 10^{-10}$, $F(H=0) = 1.26 \times 10^{-10}$, $F(K=0) = 4.20 \times 10^{-11}$, $F(L=0) = 5.22 \times 10^{-12}$, and adopting HR 2882 as primary standard star with $J = 5.53$, $H = 5.22$, $K = 5.16$, and $L = 5.12$. Table 1 reports the magnitude or the observed monochromatic fluxes for each night together with their 1σ statistical uncertainty; for the CVF data the flux at 2.18 μm and the spectral index of the best fitting power law ($F_\nu \propto \nu^{-\alpha}$) are reported.

III. DISCUSSION

Figure 2 shows the overall energy distribution of PKS 0048–09 derived from observations of 1987 January 7–9. Due to the high galactic latitude of the source ($b = -72^\circ$) and to the absence of any noticeable 2200 Å dip in the UV spectrum, no correction for interstellar extinction was applied. The data can be fitted over the whole range from 8×10^{13} to 2.5×10^{15} Hz by a single power law ($F_\nu \propto \nu^{-\alpha}$) with $\alpha = 1.00 \pm 0.01$. Separate power-law fits to the infrared, optical, and UV data yield, respectively, $\alpha_{\text{IR}} = 0.90 \pm 0.25$, $\alpha_{\text{opt}} = 0.96 \pm 0.05$ and $\alpha_{\text{UV}} = 1.39 \pm 0.03$. Infrared and optical data are fully compatible with a single power law with $\alpha_{\text{OIR}} = 0.99 \pm 0.04$ which could account also for the far end of the UV data. Note that lower frequency UV data appear to deviate significantly from the general trend. The reality of this effect is difficult to assess. In fact, problems can arise in both the absolute intercalibration of the optical and UV data and the evaluation of statistical uncertainties in each spectral range. However, no intercalibration effects of sizable magnitudes was observed so far in the whole collection of simultaneous UV-optical observations obtained by the authors. The observed deviation of the near UV data from the general trend of the energy distribution, if real, could

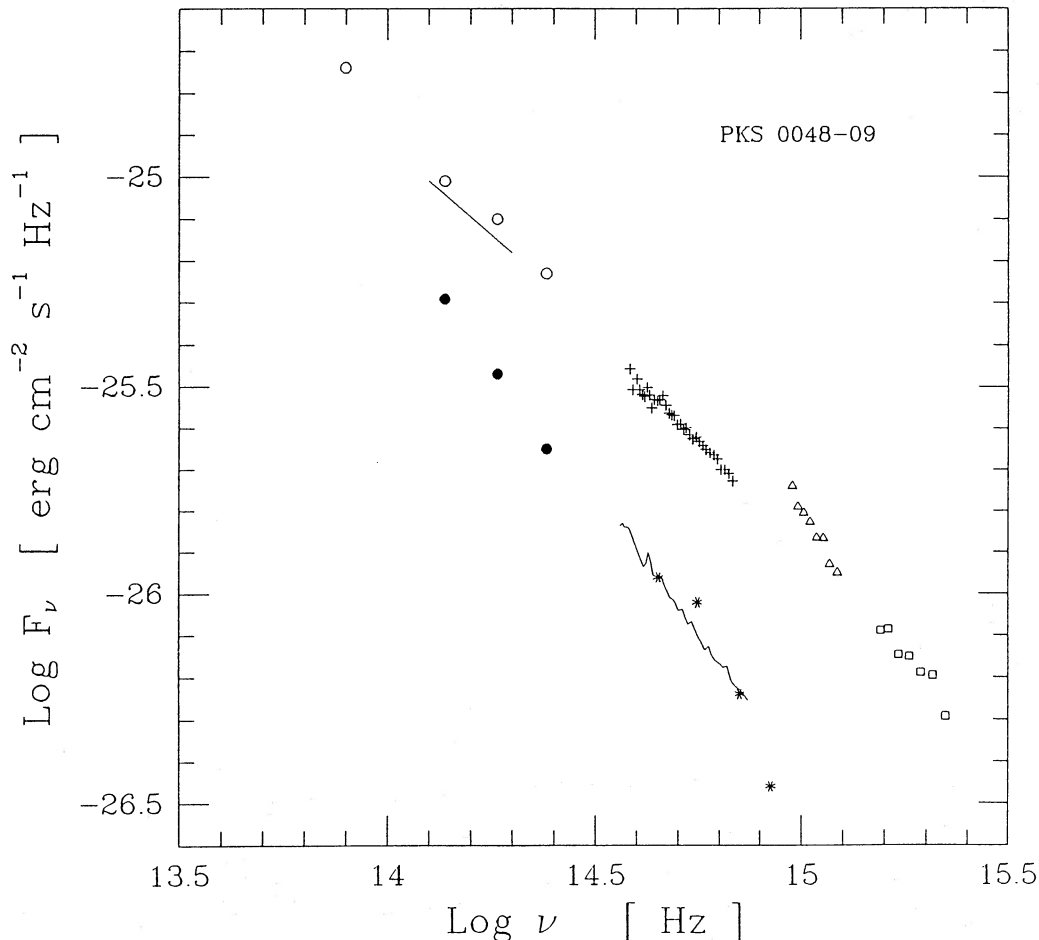


FIG. 2.—The overall energy distribution of PKS 0048–09 derived from data obtained in 1987 January 7 to 9 (upper tracing) is compared with previous nonsimultaneous data depicting a fainter state (lower tracing). Open squares ($\square$): SWP 30039, 1987 January 7.5 UT. Open triangles ($\triangle$): LWP 9886, 1987 January 8.5 UT. Plus signs (+): mean of 1987 January. Open circles ($\circ$): mean of 1987 January. Solid line: best fit of the CVF data (1987 January 9). Continuous tracing: 1986 September 12. Filled dots ($\bullet$): 1979 July (Glass 1981). Star symbol (*): 1974 August (Tapia et al. 1976).

be ascribed to a rapid (~ 0.5 days) variation of the UV emission in both intensity and spectral slope. Note that an episode of rapid optical variability (0.7 mag in 1 day) was reported by Brindle *et al.* (1986). The optical photometry of January 6-9 is marginally indicative of such a rapid variability. Another possibility is that the observed deviation be a permanent feature of the spectrum which, however, would be hard to interpret, since it is difficult to deconvolve the energy distribution in terms of a thermal component or Balmer emission, or both, superposed onto a power law.

It is interesting to compare the quasi-simultaneous observations obtained in 1987 January 7-9, when the source was in a moderately high brightness state, with previous observations. In Figure 2 the tracing representing the IDS spectrum obtained on 1986 September 12 is reported. This corresponds to a ~ 1.2 mag fainter state of the source and exhibits a spectral index 0.5 ± 0.06 steeper in the range 4000-8000 Å. The hardening of the optical slope with increasing intensity observed between 1986 September and 1987 January could be a repetitive phenomenon. In fact, both photometry by Tapia, Craine, and Johnson (1976; $\alpha_v \approx 1.4$ for the spectral region covered by our own data), and optical spectrophotometry by Wilkes *et al.* (1983) ($\alpha_v \approx 1.3$ as derived from the published tracing), show brightness level and spectral slope close to those of our 1986 observation. In its turn, the spectral slope ($\alpha_v \approx 1.0$) derived from photometry by Brindle *et al.* (1986), obtained at brightness levels bracketing that of our 1987 high state observations, is fully consistent with the hardening observed by us.

If we assume that the optical ($\alpha_v = 1.47 \pm 0.02$) and IR ($\alpha_v = 1.44 \pm 0.26$) data reported in the lower tracing of Figure 2, although pertaining to different epochs, depict the same intermediate brightness state of the source, the spectral hardening detected in the optical could be argued to extend to the near IR

range. Thus the observations presented here would provide an example of substantial hardening with increasing intensity in the whole IR-optical range for a BL Lacertae object. A similar tendency has been reported for the optical continuum of OQ 530 by Smith *et al.* (1987). For OI 090.4, spectral hardening with increasing intensity has been reported by Worrall *et al.* (1984) in the UV range while quasi-simultaneous UBv photometry indicates constancy of slope. A weak correlation between intensity and spectral slope might be present in the UV spectrum of Mrk 421 (Ulrich *et al.* 1984), while other blazars do not exhibit any clear dependence of the spectral slope on the intensity; we refer to the cases of PKS 2155-304 (Maraschi *et al.* 1986; Urry 1986) PKS 0537-441 (Tanzi *et al.* 1986) and PKS 0735+178 (Bregman *et al.* 1983).

We finally note that the visible to IR energy distribution PKS 0048-09, being accurately fitted by a single power law is remarkably at variance with the average behavior derived by Ghisellini *et al.* (1986) for a sample of 30 blazars.

In view of the importance of the dependence of spectral shape on intensity for constraining theoretical models of BL Lacertae objects, we believe that PKS 0048-09 represents a good candidate for a systematic monitoring in the optical-IR range on hours to months time scales. *IUE* observations on a target of opportunity basis are also urged in order to investigate on the occurrence of significant deviations of the UV emission from a general power law energy distribution.

We thank L. Mantegazza for obtaining *V* photometry of the object and B. Garilli for assistance with the fitting package developed by L. Chiappetti at the IFC, CNR. Useful discussions with R. Gilmozzi on the possible Earth airglow contamination of our *IUE* measurements are gratefully acknowledged.

REFERENCES

- Adam, G. 1985, *Astr. Ap. Suppl.*, **61**, 225.
 Allen, D. A., Ward, M. J., and Hyland, A. R. 1982, *M.N.R.A.S.*, **199**, 069.
 Barbieri, C., Cristiani, S., Nardon, G., and Romano, G. 1983, *Mem. Soc. Astr. Italiana*, **54**, 617.
 Bessel, M. S. 1979, *Pub. A.S.P.*, **91**, 589.
 Bohlin, R. C., and Holm, A. V. 1980, *NASA IUE Newsletter*, No. 10, p. 37.
 Bortoletto, F., and D'Alessandro, M. 1986, *Rev. Sci. Instrum.*, **57**, 253.
 Bregman, J. N., *et al.* 1983, *Ap. J.*, **276**, 454.
 Brindle, C., Hough, J. H., Bailey, J. A., Axon, D. J., and Hyland, A. R. 1986, *M.N.R.A.S.*, **221**, 739.
 Cassatella, A., and Harris, A. W. 1983, *NASA IUE Newsletter*, No. 23, p. 21.
 Falomo, R., Maraschi, L., Tanzi, E. G., and Treves, A. 1987, *IAU Circ.*, No. 4308.
 Ghisellini, G., Maraschi, L., Tanzi, E. G., and Treves, A. 1986, *Ap. J.*, **310**, 317.
 Glass, I. S. 1981, *M.N.R.A.S.*, **194**, 795.
 Kinnaird, T. D. 1976, *Ap. J.*, **205**, 1.
 Madejski, G. M., and Schwartz, D. A. 1983, *Ap. J.*, **275**, 467.
 Maraschi, L., Tagliaferri, G., Tanzi, E. G., and Treves, A. 1986, *Ap. J.*, **304**, 637.
 Pica, A. J., and Smith, A. G. 1983, *Ap. J.*, **272**, 11.
 Smith, P. S., Balonek, T. J., Elston, R., and Heckert, P. A. 1987, *Ap. J. Suppl.*, **64**, 459.
 Stone, R. P. S. 1977, *Ap. J.*, **218**, 767.
 Tanzi, E. G., Barr, P., Bouchet, P., Chiappetti, L., Cristiani, S., Danziger, J., Falomo, R., Giommi, P., Maraschi, L., and Treves, A. 1986, *Ap. J.*, **311**, L13.
 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.
 Urry, M. 1986, in *New Insight in Astrophysics*, (ESA-SP 263), p. 621.
 Usher, P. D., Kolpanen, D. R., and Pollock, J. T. 1974, *Nature*, **252**, 365.
 Wardle, J. F. C., Moore, R. L., and Angel, J. R. P. 1984, *Ap. J.*, **279**, 93.
 Wilkes, B. J., Wright, A. E., Jauncey, D. L., and Peterson, B. A. 1983, *Proc. Astr. Soc. Australia*, **5**, 2.
 Worrall, D. M., Puschell, J. J., Rodrigues-Espinosa, J. M., Bruhweiler, F. C., Miller, H. R., Aller, M. F., and Aller, H. D. 1984, *Ap. J.*, **286**, 711.

Note added in proof.—With reference to the flux excess reported at 2400-3000 Å, we note that recent papers suggest the possibility of a miscalibration of the LWP *IUE* camera at low flux levels (P. M. Gondalekhar and G. Ferland, in *Scientific Accomplishments of IUE*, ed. Y. Kondo (Dordrecht: Reidel) [1987]; J. M. George, *Proc. IUE Symposium: A Decade of UV Astronomy with IUE Satellite*, in press [1989]).

P. BOUCHET: European Southern Observatory, La Silla, Chile

R. FALOMO: Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 5, Padova, Italy

L. MARASCHI and A. TREVES: Dipartimento di Fisica, Via Celoria 16, Milano, Italy

E. G. TANZI: Istituto di Fisica Cosmica, CNR, Via Bassini 15, Milano, Italy