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PG 1553+11: A BRIGHT OPTICALLY SELECTED BL LACERTAE OBJECT*

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ABSTRACT

A detailed study of the bright optically selected BL Lacertae object PG 1553+113 is presented. Ultraviolet observations, obtained during a high state of the source, together with simultaneous optical spectrophotometry and near-IR photometry allow us to examine the spectral flux distribution from 8×10^{13} to 2.5×10^{15} Hz. This distribution is compared with that derived from quasi-simultaneous observations obtained when the source was a factor ~ 3 fainter. It is found that in the higher state the spectrum can be described by two power laws connected by a break at $\sim 10^{15}$ Hz, while in the low state the shape is more complex. The overall spectrum of the object is compared with the average energy distribution of X-ray and radio-selected BL Lac objects, showing that it is closer to the former class.

Key words: BL Lacertae objects–galaxies: individual (PG 1553+11)

1. Introduction

The Palomar Green survey of UV-excess stellar objects (Green, Schmidt, and Liebert 1986) provided a large sample of bright ($m_{pg} \lesssim 16.1$) extragalactic objects over about one-fourth of the sky. About 100 are QSO and only four are BL Lacertae objects (hereinafter BLL). Three of these (OJ 287, 2A 1219+30, and OQ 530) were previously known. PG 1553+113 is the only one which was discovered with the survey. The BLL classification was suggested by the featureless spectrum (Miller and Green 1983) together with significant ($m_p = 13.2$–15.0) optical variability (Miller *et al.* 1988). No polarization measurement is known to us. Since most of the BLL are found as counterparts of either radio or X-ray sources, it is of interest to compare the properties of PG 1553+113 with those of radio and X-ray-selected BLL.

In the course of a monitoring program of BLL (see, e.g., Tanzi *et al.* 1989), we found the object in a (relatively) bright state on 1988 August 3. This prompted us to obtain far-UV observations together with simultaneous optical spectrophotometry and near-IR photometry. This high state is compared with previous quasi-simultaneous UV and optical data obtained when the source was a factor 3 fainter. The energy distribution is discussed and comparison is made with the average spectral properties of X-ray and radio-selected BLL.

2. Observations and Data Analysis

2.1 *UV data*

In the UV range the source was observed in August 1988 (see Table 1), both with the short-wavelength prime (SWP) and with the long-wavelength prime (LWP) cameras aboard the International Ultraviolet Explorer (IUE). The source was centered in the offset mode with the large aperture ($10'' \times 20''$ oval) at coordinates $\alpha(1950) = 15^{h}53^{m}20^{s}.74 \pm 0^{s}.04$ and $\delta(1950) = +11°20'05''.7 \pm 0''.8$ as measured on a blue paper copy of POSS. The combined (SWP 34008 + LWP 13782) spectrum obtained on August 1988 is reported in Figure 1. No emission or absorption features are apparent.

Six further IUE spectra taken in 1982–87 (see Table 2) were retrieved from archives (see also Miller *et al.* 1988). All the IUE data have been analyzed using the optimal extraction procedure by Horne (1986). First the background of the line-by-line (LBL) spectrum was cleaned using a median filter to remove spikes and other blemishes, then the background under the object spectrum is estimated, fitting with a 2nd-order polynomial the spatial profile of the LBL image at each wavelength. At this stage the optimal extraction is performed using a window of eleven (21 for the 110-LBL files) scan lines centered on the object. The signal-to-noise ratio (S/N) of the optimal

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*Based on observations collected at the European Southern Observatory, La Silla (Chile) and with the International Ultraviolet Explorer at the European Space Agency Tracking Station in Villa Franca (Spain).

extracted spectra was 10% to 30% higher, with respect to the standard IUESIP extraction, and most defects affecting the spectrum could be removed. The extracted spectra were then calibrated using curves provided by Bohlin and Holm (1980), Cassatella and Harris (1983), and Cassatella 1988.

TABLE 1

Journal of Observations

Date	(UT)	Instrument	Range	Notes[a,b]
1986	Sep 11.8	ESO 1.5m + B&C + IDS	4100-8300 Å	V = 15.3 ± 0.1 α = 1.13 ± 0.03
1987	Aug 30.0	ESO 1.5m + B&C + CCD	4000-7300 Å	V = 14.6 ± 0.1 α = 1.23 ± 0.01
	31.0	ESO 1.5m + B&C + CCD	4000-7300 Å	V = 14.6 ± 0.1 α = 1.22 ± 0.02
1988	Aug 01.9	IUE + SWP	1200–1900 Å	F(1500Å) = 210
	02.8	IUE + LWP	2000–3200 Å	F(2500Å) = 160
	03.0	ESO 1.5m + B&C + CCD	4100-7400 Å	V = 14.2 ± 0.1 α = 1.07 ± 0.02
		ESO-MPI 2.2m + InSb phot	J, H, K, L	K = 10.93 ± 0.01 α = 0.76 ± 0.06
	04.0	ESO 1.5m + B&C + CCD	4100-7400 Å	V = 14.2 ± 0.1 α = 1.07 ± 0.03
		ESO-MPI 2.2m + InSb phot	J, H, K, L	K = 10.94 ± 0.01 α = 0.75 ± 0.07
	05.0	ESO 1.5m + B&C + CCD	4100-7400 Å	V = 14.2 ± 0.1 α = 1.07 ± 0.03
		ESO-MPI 2.2m + InSb phot	J, H, K, L	K = 10.96 ± 0.01 α = 0.76 ± 0.05
	7.0	ESO 1.5m + B&C + CCD	6500–9800 Å	poor photometry
	8.0	ESO 1.5m + B&C + CCD	3800–5500 Å	FWHM = 4 Å
	9.0	ESO 1.5m + B&C + CCD	5500–7200 Å	FWHM = 4 Å

[a] Spectral index α is defined as $F_\nu \propto \nu^{-\alpha}$ (quoted errors are 90% confidence level)
[b] Flux is in units of 10^{-16} erg cm^{-2} s^{-1} Å^{-1}

Some regions of the spectra heavily affected by camera flaws and cosmic-ray hits were excluded. (a) The region from 1630 Å to 1680 Å of SWP 18148, where a wide bright spot in the LBL image produces a spurious emission line (misidentified as Lyman-α at z = 0.36 by Miller and Green 1983); (b) the region at λ < 2600 Å of LWP 9081 which appears very noisy in the LBL file; (c) the region around 1360 Å of SWP 34008 where a hot spot almost centered on the spectrum produces a spurious line at ~ 1360 Å.

2.2 *Optical Data*

Optical spectrophotometry of the source has been obtained since September 1986 with the 1.5-m telescope of the European Southern Observatory (ESO) at La Silla (Chile). A journal of the observations is given in Table 1. A Boller and Chivens spectrograph was used with the CCD detector from 1987, while an Image Dissector Scanner (IDS) was employed for the September 1986 observations. Spectrophotometry was taken at low resolution (FWHM ≈ 15 Å) using an aperture of 8 × 8 arc sec. The accuracy of the photometry, as derived from several observations of standard stars (Stone 1977; Baldwin and Stone 1984), is better than 10%. Reductions of optical

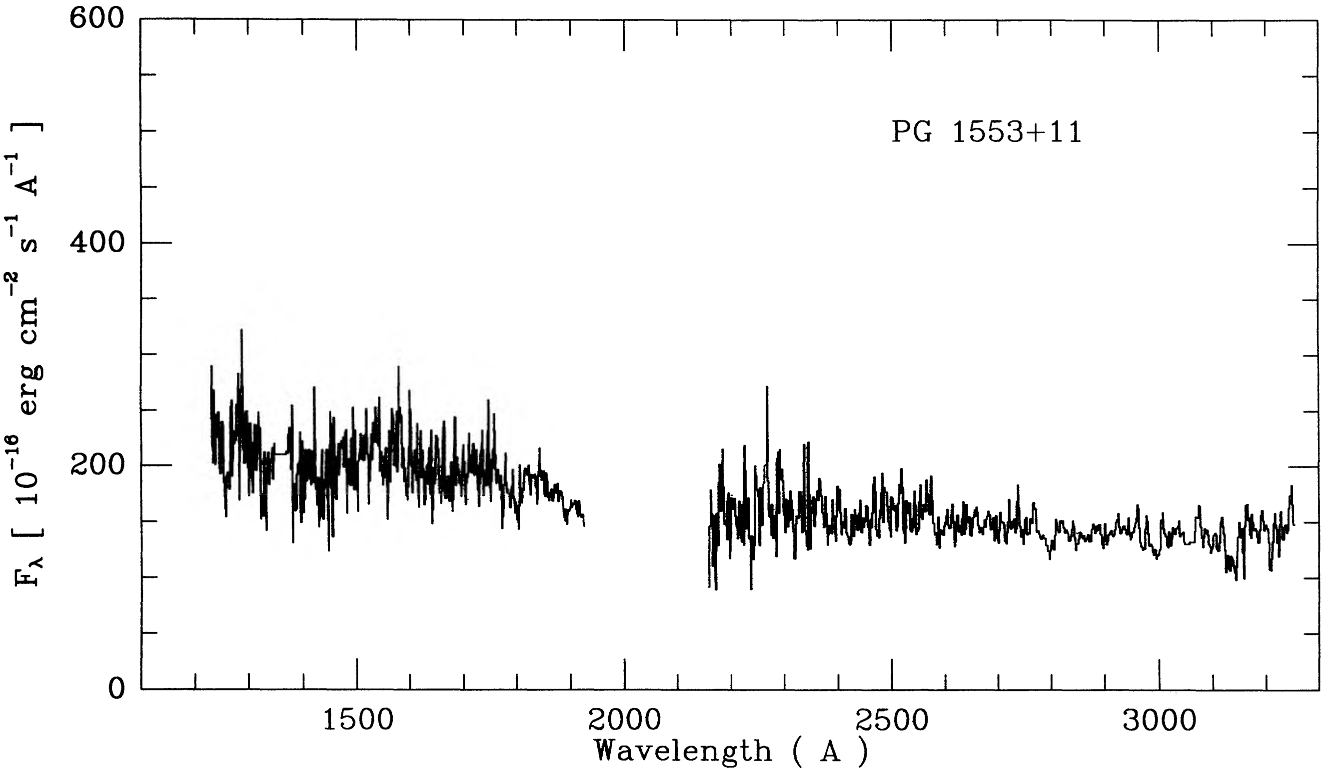

FIG. 1–The UV spectrum (SWP 34008 + LWP 13782) of PG 1553+11 obtained on 1988 August 1 and 2. The spurious features around 1360 Å have been removed (see text).

data were performed by using IHAP and MIDAS reduction systems following standard procedures.

On 1988 August 8 and 9 medium-resolution (~ 4 Å) spectroscopy was obtained in the range 3800 Å–7200 Å in order to search for emission or absorption features. For these spectra double exposures and optical extraction methods, following again the procedure outlined by Horne (1986), were adopted in order to improve the detectability of faint features. The combined averaged medium resolution spectrum is shown in Figure 2. The continuum appears very regular; no emission or absorption lines with equivalent widths $\gtrsim$ 1 Å are apparent.

TABLE 2

Ultraviolet Observations

Date	Image	exp. (min)	Flux^a	α^b
1982 Sep 29.3	SWP 18148	144	135 ± 26	1.34 ± 0.16
29.1	LWR 14289	240	94 ± 16	
1986 Sep 15.0	SWP 29216	210	52 ± 16	1.32 ± 0.22
15.2	LWP 9081	185	31 ± 10	
1987 Apr 17.5	SWP 30798	170	78 ± 16	1.94 ± 0.12
17.7	LWP 10595	175	78 ± 10	
1988 Aug 01.9	SWP 34008	334	197 ± 21	1.50 ± 0.10
02.8	LWP 13782	160	156 ± 16	

[a] Mean fluxes in the range 1250–1950 (SWP) and 2400–2300 (LWP) in units of 10^{-16} erg cm^{-2} s^{-1} Å^{-1}

[b] Spectral index α ($F_\nu \propto \nu^{-\alpha}$) for the SWP + LWP range

2.3 *Near-IR Data*

Broad-band *J*,*H*,*K*, and *L* photometry was acquired on 1988 August 3 to 5 (see Table 1) with the ESO-MPI 2.2-m telescope equipped with an InSb detector. A 15″ circular aperture, with chopper throw of 20″ in the E–W direction, was used. Statistical 1 σ errors are less than 0.02 mag for the bands *J*, *H*, and *K* and about 0.15 mag for band *L*. Conversion to flux units was performed using the zero-magnitude fluxes given in Falomo *et al.* (1988). The total uncertainties of the fluxes in the near-IR, accounting both for statistical and systematic flux calibration errors, is of ~ 0.05 mag for *J*, *H*, and *K* and 0.20 mag for *L* (Bersanelli, Bouchet, and Falomo 1990).

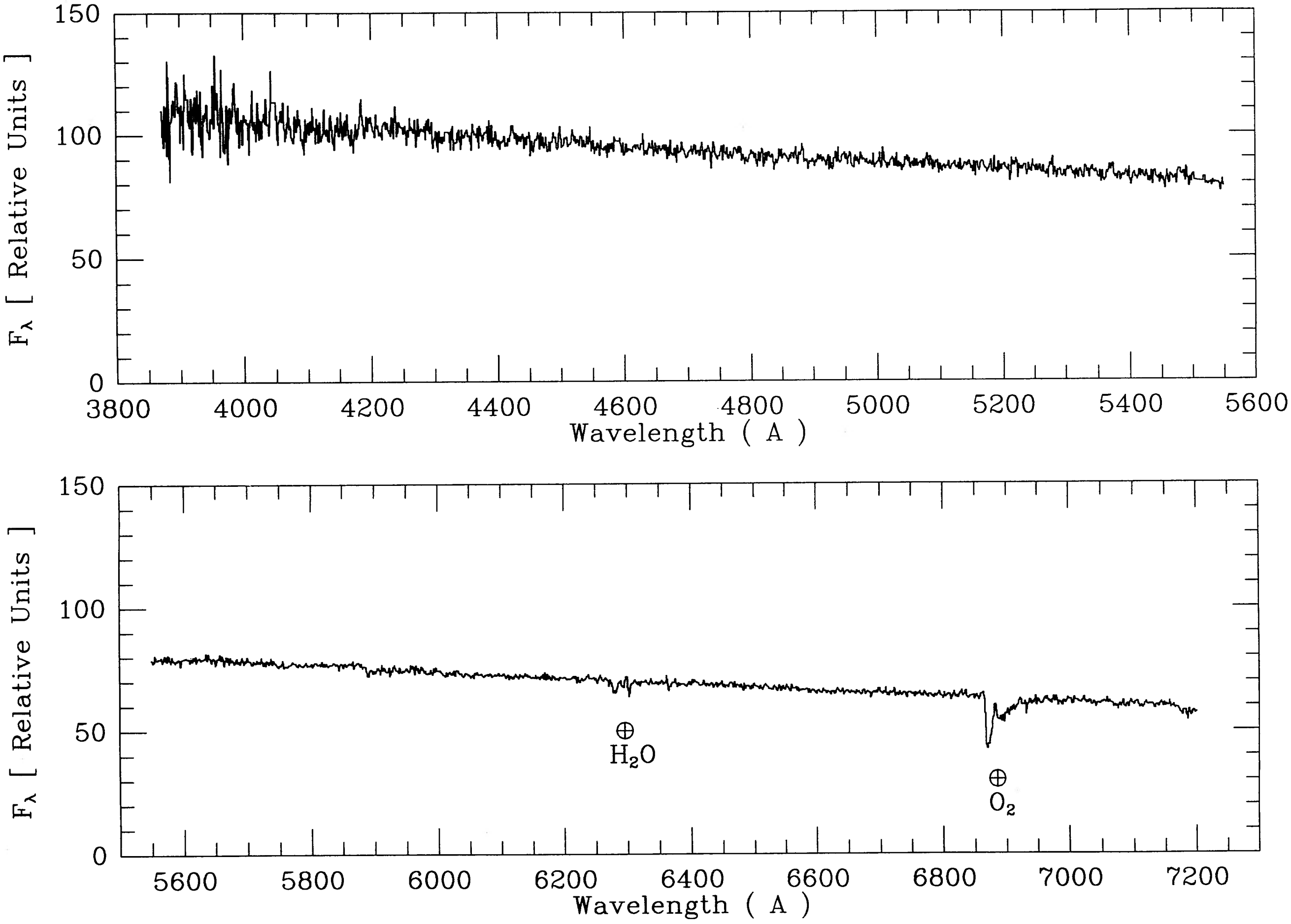

FIG. 2–The medium-resolution spectrum of PG 1553+11 of 1989 August 8, 9. Absorptions due to atmospheric bands are marked by ⊕. The spectrum is featureless with an equivalent-width upper limit of ~ 1 Å.

3. Discussion

The simultaneous UV-optical and near-IR observations of 1988 August 1 to 8 allow us to study the spectral flux distribution from 8×10^{13} to 2.5×10^{15} Hz (see Fig. 3). Because no variability was present at visible and infrared frequencies from August 3 to 5, the averaged data have been considered. Optical and UV fluxes were derived binning the spectrum in intervals of ~ 100 Å. The undereddened flux distribution exhibits a steepening between the infrared and optical bands, $\Delta\alpha \simeq 0.3$, and between the optical and UV one, $\Delta\alpha \simeq 0.5$ (see Tables 1 and 2). Spectral fluxes were corrected for interstellar reddening assuming $A_V = 0.2$, as deduced from the hydrogen column density $N_H = 3.6 \times 10^{20}$ cm^{-2} (Stark *et al.* 1984) for $N_H/E_{B-V} = 5.8 \times 10^{21}$ (Bohlin, Savage, and Drake 1978). The interstellar extinction curve of Savage and Mathis (1979) for the optical-UV region and its extension to IR by Whittet (1988) was used.

The dereddened IR and optical spectral flux distribution (see Fig. 3) is quite smooth from IR to UV frequencies. However, a single power-law model ($F_\nu \propto \nu^{-\alpha}$) does not fit well the data in the whole range. The near-IR to optical data can be well fitted by a single power law with $\alpha = 0.80 \pm 0.07$, while in the UV range a much steeper power law ($\alpha = 1.27 \pm 0.05$) is required. A break ($\Delta\alpha \simeq 0.5$) is thus present around 10^{15} Hz. The spectral break ($\Delta\alpha \approx 0.3$) between near-IR and optical undereddened fluxes (see above) is essentially removed by the reddening correction. This seems to occur rather commonly in BLL (Tanzi *et al.* 1989).

It is interesting to compare this spectral flux distribution with that obtained combining optical and archival UV observations, although not strictly simultaneous, of September 1986, when the source was a factor 3 fainter (see also Tables 1 and 2; note that in Table 1 the spectral index refers to fits of data not corrected for reddening). A power-law fit to the September 1986 dereddened optical data yields $\alpha = 0.90 \pm 0.03$, while the dereddened UV fluxes are fitted (though poorly) by a power law with a spectral index $\alpha \simeq 1.1 \pm 0.2$.

The examination of the spectral flux distribution in the two states indicates that a larger flux variation is present in the UV (a factor ~ 4.3) with respect to that in the optical range (a factor ~ 2.7). The optical spectral shape is essentially unchanged; that in the UV (though the uncertainty is large) appears close to, or even flatter than, that in the higher state. Unless the energy distribution in the low state is affected by the nonstrict simultaneity between optical and UV observations, one must conclude that the steepening in the low state occurs between ~ 4000 Å and ~ 3000 Å, a region where no observations are available. Therefore, contrary to what occurs in the higher state, it seems difficult to describe the optical to UV energy distribution with two power laws connected by a single break. The change in slope occurring at wavelengths shorter than ~ 4000 Å is consistent with the findings of Miller *et al.* (1988) that there is essentially no change in the $(B-V)$ color but that there are changes of $(U-B)$ during flux variations of 1 magnitude.

In order to discuss the overall spectral properties of the

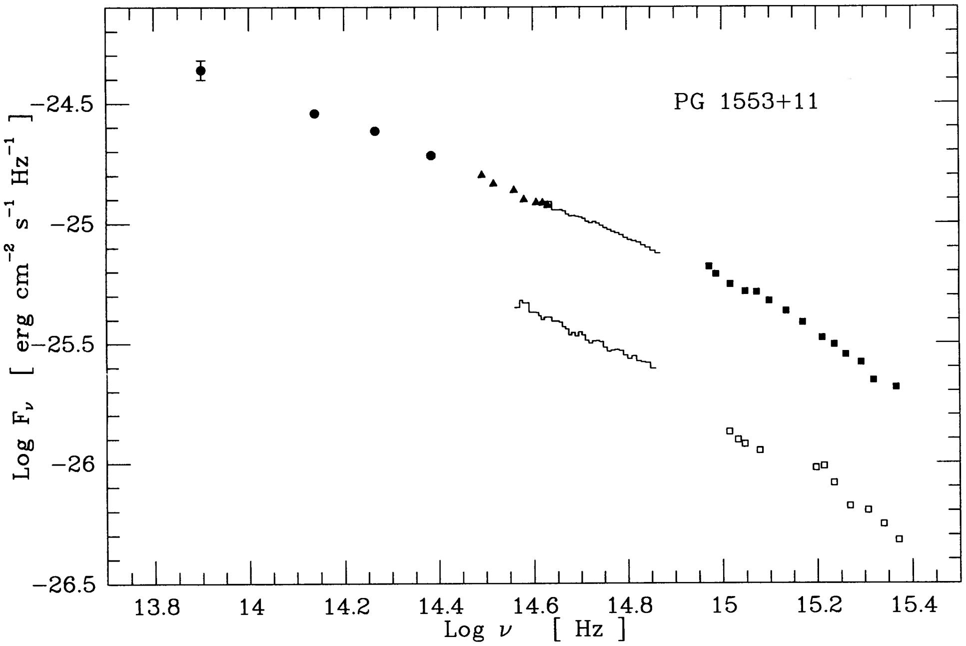

FIG. 3–Spectral flux distribution of PG 1553+11 in two brightness states: upper tracing—average values of 1988 August 2–5; the filled triangles represent observations of 1988 August 6 scaled to match the flux of 1988 August 3 to 5; lower tracing—1986 September 12–15. Details on the data are reported in Table 1 (optical and IR) and Table 2 (UV). All fluxes have been dereddened (see text).

source we consider observations at frequencies not already treated here, namely in the radio, infrared, and X-ray bands. As for radio measurements it is found that the position of the radio source MG 1555+1110 (Bennet *et al.* 1986) is consistent within 2σ with the optical one and we propose that it is its radio counterpart. The radio flux at 5 GHz is 504 mJy. PG 1553+113 probably coincides also with the IRAS source 1553+113 ($F_{100\ \mu\mathrm{m}}$ = 493 mJy; Impey and Neugebauer 1988). In the X-ray there is a very likely coincidence with the source appearing in the N.10608 observation of the Einstein Observatory database. The object was observed on 1981 March 12 with an integration time of 3352 sec and exhibited a count rate of 1.27 cts/s. Assuming a hydrogen column density of 3.6×10^{20} (see above), and a power-law slope of index $\alpha = 1$, the X-ray flux at 2 keV turns out to be 4 μJy, which puts the object among the brightest BL Lacs in the X-ray band (see, e.g., Maraschi and Maccagni 1988).

For a comparison of the spectral flux distribution with that of other BL Lacs we refer in particular to the paper of Ghisellini *et al.* (1986) who considered 33 blazars observed in the far UV. In Table 3 we report the spectral indices of PG 1553+11 and the average ones, distinguishing radio and X-ray-selected objects. Because radio and X-ray observations are not taken simultaneously with UV data we computed radio-UV and UV-X-ray spectral indices using minimum and maximum values for the UV flux (see Table 2). It is apparent that both the near-IR and optical spectral indices and the radio-UV and UV-X-ray indices are in the typical range of X-ray-selected objects. The UV index is, however, intermediate between the two classes. Thus, although PG 1553+113 was discovered in an optical survey, its spectral characteristics appear close to those of X-ray-selected BLL.

TABLE 3

Comparison of Spectral Indices

	PG 1553+11	X–ray selected[a]	Radio selected[a]
α_{IR}	0.71	0.51 ± 0.10	1.06 ± 0.06
α_{OPT}	0.83	0.83 ± 0.14	1.51 ± 0.10
α_{UV}	1.1–1.7	0.87 ± 0.12	1.56 ± 0.11
α_{RU}	0.37–0.48	0.39 ± 0.05	0.55 ± 0.02
α_{UX}	096–1.19	1.02 ± 0.09	1.35 ± 0.05

[a] average values from Ghisellini *et al.* (1986)

Most of the X-ray-selected BLL show clear evidence of a host galaxy (see, e.g., Stocke *et al.* 1985). In the case of PG 1553+11 the stellar appearance, as indicated by the examination of the Palomar plate, and the absence of stellar absorption features in the optical spectrum, with an equivalent-width upper limit of 1 Å, give no indication for the presence of a host galaxy. This suggests that the nonthermal component is dominant ($\gtrsim$ 90%) with respect to the host galaxy and would imply $z \gtrsim 0.1$ if the host galaxy is a giant elliptical. It is worth noting that in this respect PG 1553+11 may be similar to two other X-ray-selected BLL: PKS 2155–30 and H1722+119. The three objects are among the brightest of the class (m_V = 13–15); they have no reliable redshift measurements and no indication of host galaxy. In this regard see the recent results of Falomo and Melnick (1989) and Falomo, Melnick, and Tanzi (1990) on PKS 2155-30 and of Brissenden *et al.* (1990) on H1722+11. From the relatively bright apparent magnitude of the objects and the lack of host galaxy signature it could be argued that either the host galaxy is very underluminous with respect to giant ellipticals found in many BLL (see, e.g., Ulrich 1989) or they are distant ($z \gtrsim 0.5$), very luminous ($L \sim 10^{46} - 10^{47}$ erg/s), and possibly strongly beamed objects. High-resolution imaging and spectroscopy of PG 1553+11 as well as of PKS 2155–30 and H1722+11 are needed to elucidate this point.

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