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BALMER LINE VARIATIONS IN THE RADIO-LOUD ACTIVE GALACTIC NUCLEUS PG 1512+370

P. ROMANO,[1,2] P. MARZIANI,[3] AND D. DULTZIN-HACYAN[4]
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ABSTRACT

We present spectroscopic observations of the quasar PG 1512+370, covering the Hβ line spectral range and collected at moderate resolution (2–7 Å FWHM) from 1988 to 1996. The observations show that the blue wing of the Hβ broad profile component has changed significantly in flux and shape between 1988 and 1990 and between 1995 and 1996. A displaced blue peak on the Hβ profile, visible in 1988, but not in the 1990–1995 spectra, is revealed again in one of the spectra obtained in 1996. The blue peak (in both the 1988 and 1996 spectra) is centered at $\Delta v_r \approx -3000^{+500}_{-500}$ km s^{-1} from the rest frame defined by the narrow component of Hβ, and the [O III] $\lambda\lambda$4959, 5007 lines.

We discuss several conflicting interpretations of the data. We find that the variability of the Hβ blue wing is consistent with Balmer line emission from regions whose motion is predominantly radial, if variations of the blue wing are a response to continuum changes. Alternatively, we note that observed Hβ line profile variations are consistent with a variable line component as in a "binary black hole" scenario. More frequent observations of Hβ are needed to distinguish among these hypotheses.

Subject headings: galaxies: active — galaxies: kinematics and dynamics — galaxies: nuclei — line: profiles — quasars: emission lines — quasars: individual (PG 1512+370)

1. INTRODUCTION

Understanding the structure of the inner parsec of quasars, which includes the line- and continuum-emitting regions, has proved elusive. Reverberation mapping techniques have been applied to several low-luminosity radio-quiet active galactic nuclei (AGNs). Although they required large amounts of telescope time, they set on a firm ground basic aspects of the broad line region (BLR), i.e., the stratification of ionization (see Netzer & Peterson 1997, Peterson 1993, Penston 1991, for reviews). Other results are unfortunately more ambiguous. One reason for the ambiguity resides in our poor understanding of the constraints on the inputs to the line formation processes in the BLR (Baldwin 1997). Statistical studies of line profiles have in principle the advantage of an approach less dependent on the poorly known physical conditions of the BLR. However, they are as yet plagued by small-number statistics and by the difficulty of obtaining a uniform sample, in terms of observational (e.g., signal-to-noise ratio [S/N]) and intrinsic properties (such as optical luminosity; see Baldwin 1997 for a recent review).

Radio-loud AGNs have been associated to an extreme in the distribution of parameters of radio-quiet AGNs (Brotherton 1996; Corbin & Boroson 1996). However, Marziani et al. (1996, hereafter M96) have shown that radio-loud AGNs with detected superluminal motion and apparent velocity $\beta_{\rm app} \gtrsim 10$ show C IV λ1549 profiles with low EW and remarkably strong redward asymmetry. There is no equivalent phenomenology in radio-quiet objects. Also, widely spaced double-peaked profiles appear almost exclusively in radio-loud AGNs (see Eracleous 1997 for a critical review; Eracleous & Halpern 1994). Statistical analysis of Balmer line profiles suggests systemic, kinematic, and structural differences in the BLR of (at least some) radio-quiet and radio-loud AGNs (M96; Romano et al. 1996).

There is therefore little evidence that the basic reverberation and profile analysis results can be extended straightforwardly to radio-loud or high-luminosity AGNs. In the handful of radio-loud AGNs known to have variable profiles, the profiles are often peculiar (i.e., double-peaked), as in the cases of 3C 390.3 (Veilleux & Zheng 1991), its twin 3C 382, OQ 208 (Marziani et al. 1993), and Pictor A (Sulentic et al. 1995; Halpern & Eracleous 1994). This is different from the case for radio-quiet AGNs, since monitored Seyfert nuclei do not show double-peaked line profiles. The most common profile among radio-loud AGNs, however, is not the extremely broad, double-peaked profile observed in Arp 102B; instead, it is regular, single peaked, and redward asymmetric with redward peak displacement (M96; class AR, R according to Sulentic 1989). The double-peaked profiles are probably not representative of the radio-loud AGNs as a class.

The low-redshift (heliocentric $z = 0.3707 \pm 0.0002$; M96) radio quasar PG 1512+370 (B2 1512+37, 4C 37.43) has been frequently observed at optical wavelengths (O'Brien & Gondhalekar 1991 and Boroson & Green 1992, among others). The Hβ broad profile component (H$\beta_{\rm BC}$) of PG 1512+370 belongs to the class AR, R for most epochs of observations; hence, it is fairly typical of radio-loud AGNs. Variability of broad UV lines C IV λ1549 and Lyα has been reported in 1991 from *IUE* observations (O'Brien & Gondhalekar 1991). These authors suggested the possibility of moderate Hβ line flux variations from published data [EW(H$\beta_{\rm BC}$) appeared to vary by $\approx$20%].

In this paper, we report the discovery of Hβ line profile variations in PG 1512+370 and, in particular, variation of the H$\beta_{\rm BC}$ blue wing and of a secondary "blue peak" from the analysis of spectra collected from 1988 to 1996 (§ 2). We

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[1] Department of Physics and Astronomy, Gallalee Hall, Tuscaloosa, AL 35487.

[2] Department of Astronomy, Ohio State University, 174 West 18th Avenue, Columbus, OH 43210; promano@astronomy.ohio-state.edu.

[3] Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italia; marziani@astrpd.pd.astro.it.

[4] Instituto de Astronomia, UNAM, Apdo Postal 70-264, Mexico DF 04510, Mexico; deborah@astroscu.unam.mx.

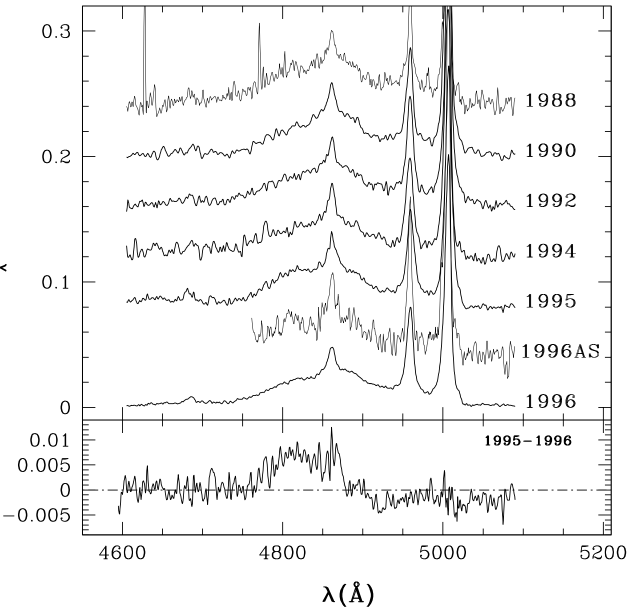

FIG. 1.—(*Upper panel*) Optical spectra of PG 1512+370 obtained during 1988, 1990, 1992, 1994, 1995, and 1996 (see Table 1 for the observation log). Specific flux F_λ is in units of 6.9×10^{-15} ergs s^{-1} cm^{-2} Å^{-1} (i.e., the average flux of [O III] λ4959 used as a scaling factor). The spectra have been vertically offset for clarity, with the exception of the spectrum labeled "1996." (*Lower panel*) Difference between the 1995 and 1996 spectra. Units are the same as for the upper panel.

will attempt to explain the H$\beta_{\rm BC}$ profile and its variations as a result of (1) accretion disk emission (§ 3.1), (2) radially moving gas (§ 3.2), or (3) a binary BLR (§ 3.3).

2. DATA AND RESULTS

We summarize the available data in Table 1. The initial reduction followed the standard IRAF procedures, which include bias subtraction, flat fielding, wavelength calibration, correction for extinction, and flux calibration (see also M96 and references therein for further details). The spectra have been corrected for redshift, the individual redshifts being determined as the average of the peaks of the Gaussian fits to the upper half of Hβ and [O III] λλ4959, 5007.

The upper panel of Figure 1 shows the optical spectra for PG 1512+370 in the Hβ region. The spectra have been continuum subtracted by fitting a low-order polynomial through wavelength regions uncontaminated by emission lines. Most of the weight in the continuum fit has been assigned to (1) the region around 4200 Å as adopted for the quasar composite spectrum by Francis et al. (1991) and (2) to the red side of [O III] λ5007. Other wavelength regions around 4020 Å and, with decreasing weight, around 4620 Å have been included in the fit when available. The spectra have then been scaled to the same flux as [O III] λ4959. We did not choose λ5007 because of the intrinsically larger errors due to the presence of the telluric *B* band at its red side. The scale factor determined on the basis of [O III] λ4959 is affected by the extended appearance of the [O III] emission (diameter ≈ 4″; Durret et al. 1994). On the other hand, the Hβ narrow profile component (H$\beta_{\rm NC}$) flux is difficult to measure because the underlying H$\beta_{\rm BC}$ is variable. As a result, measured fluxes are thought to be accurate within ±10% at a 3 σ confidence level. The procedure to remove the contribution of Fe II$_{\rm opt}$ (which is minimal; see, e.g., Boroson & Green 1992), He II λ4686, H$\beta_{\rm NC}$, and [O III] λλ4959, 5007 from the Hβ profile is described in M96. Table 2 reports measurements taken on the cleaned H$\beta_{\rm BC}$ line.

The only signicant change of *total* H$\beta_{\rm BC}$ flux recorded in our spectra occurred probably between 1988 and 1990, when it was ≈30% of the 1988 flux. The larger decrease is observed in the blue wing of H$\beta_{\rm BC}$ with a possible smaller decrease in the H$\beta_{\rm BC}$ red wing. Between 1990 and 1996 the H$\beta_{\rm BC}$ flux remained constant within the observational uncertainties. No shape change is noticeable in the 1990, 1992, and 1994 spectra. At these times, there is no peak at $\Delta v_r \approx -3000$ km s^{-1} (the "blue peak") or blue shoulder visible, and the H$\beta_{\rm BC}$ profile can be classified as AR, R according to Sulentic (1989). However, the line profile showed remarkable changes between 1988 and 1990, as well as between 1995 and 1996.

1. The blue peak is visible in the 1988 spectrum but is apparently absent in 1990, when the total H$\beta_{\rm BC}$ flux is also significantly lower.
2. The blue wing appears more prominent in the 1995 spectrum but depressed in the 1996 spectrum obtained at San Pedro Martir, with a blue wing fractional flux decrease of ≈20%. This variation resembles the one that occurred between 1988 and 1990, save that the total H$\beta_{\rm BC}$ flux did not change appreciably in the 1995 and 1996 observations.

The lower panel of Figure 1 shows the difference between the 1995 and 1996 spectra in the Hβ region. The slight depression in the 4925–5025 Å region is due to the extended nature of [O III], as a different contribution from extranuclear [O III] probably fell within the slit in the 1995 and 1996 spectra. To compute the probability that the observed

TABLE 1

DATA SAMPLE FOR PG 1512+370

Observatory	Dates	Telescope Aperture (m)	Spectrograph	Exposure Time (s)	Slit Width (arcsec)	P.A. (°)	Spectral Resolution (Å)	Detector	Reference
La Palma	1988 May 5	2.5	IDS	8000	1.6	[a]	3	235 camera	1
KPNO	1990 Sep 20	2.1	Gold	2700	1.5	0	6.5–7	TI 800 × 800	2
KPNO	1992 Jul 8	4.0	[a]	1200	1.7	90	6	Tek 1024 × 1024	3
Calar Alto	1994 Apr 11	2.2	B&Ch	4800	2.0	90	5.6–8	Tek 1024 × 1024	4
Calar Alto	1995 May 1	2.2	B&Ch	5400	1.6	90	6	Tek 1024 × 1024	5
Asiago...................	1996 Apr 20	1.8	B&Ch	7200	2.0	90	2	Thomson 7882	5
San Pedro Martir......	1996 May 20	2.2	B&Ch	8400	2.1–2.6	90	6–10	CCDTEK	5

NOTE.—(1) Jackson, Penston, & Pérez 1991, (2) Boroson & Green 1992, (3) Eracleous & Halpern 1994, (4) M96, and (5) this work.

[a] Not recorded.

TABLE 2

PG 1512+370 Hβ LINE MEASUREMENTS

JD	EW(Hβ) (Å)	Hβ Flux[a]	Hβ Flux[a] (Blue Wing)	Hβ Flux[a] (Red Wing)	Continuum Specific Flux[b]
2,447,287	94	6.72	3.49	3.21	0.73
2,448,155	124	5.27	2.40	2.87	0.43
2,448,812	105	5.23	2.44	2.79	0.49
2,449,839	65	5.18	2.87	2.31	0.71
2,450,194[c]......	75[c]	4.65[c]	...	...	0.49
2,450,224	120	5.03	2.37	2.66	0.53

[a] Hβ flux in units of [O III] λ4959 flux.

[b] Continuum specific flux in units of 10^{15} ergs s^{-1} cm^{-2} Å^{-1}.

[c] Hβ profile in the Asiago spectrum is truncated at $\approx$4750 Å. EW and reported flux values are lower limits.

change in line profile shape is due to random noise fluctuation, we first estimated the 3 σ noise level from the observed maximum noise fluctuations over the average signal in the rest-frame range 5060–5100 Å (much larger than the noise correlation length $\lambda_{C,\mathrm{noise}} \approx 4$ pixels). We rebinned the spectrum (over the wavelength range where we observe a change) with a step $\approx \lambda_{C,\mathrm{noise}}$. We then multiplied the probability that the change in amplitude for each bin is due to noise (which is assumed constant over the Hβ_{BC} line wing). We find the probability that the blue wing change between 1995 and 1996 due to fluctuations is negligibly small. Similar considerations apply to the 1990–1988 Hβ_{BC} line profile difference (not shown in Fig. 1).

The remaining question at this point is whether the blue peak may or may not be variable in radial velocity. The ability to resolve the "blue shoulder" into a "blue peak" depends on the spectral resolution of the data. The 1988 and 1996 (Asiago) spectra have resolutions of 3 Å and 2 Å FWHM, respectively. The blue peak is well visible at $\Delta v_r \approx -2960^{+600}_{-250}$ km s^{-1} (in 1988) and $\Delta v_r \approx -3400^{+750}_{-400}$ km s^{-1} (in 1996), with respect to the radial velocity of Hβ_{NC}. The 1995–1996 difference has a broad Gaussian shape, with maximum at $\lambda \approx 4814$ Å. Radial velocity values of the blue peak measured in 1988, 1995, and 1996 are therefore consistent. The possibility that the blue peak is present in the 1990, 1992, and 1994 spectra but not visible because of the lower resolution cannot be ruled out. After all, the blue flat top observed in the 1996 San Pedro Martir spectrum is resolved as a blue peak in the 1996 Asiago spectrum, collected 30 days earlier, when the blue wing appeared depressed. Two interpretations seem possible.

1. The blue peak is a component of Hβ_{BC} that is more variable than the rest of Hβ_{BC}, at approximately constant Δv_r. In this case, the blue peak (1) may be due to a flux redistribution within Hβ_{BC} unrelated to continuum changes or (2) may be a structure produced by response to continuum variation. Both the 1988 and 1995 spectra (when the blue wing was more prominent) show the highest continuum fluxes. This suggests that an enhancement of the blue wing is related to an increase of the continuum level. However, as the total Hβ_{BC} flux did not change significantly in all our spectra obtained between 1990 and 1996, it is also possible, albeit less likely, that we are observing a line flux redistribution unrelated to continuum variations (as in NGC 5548; Wanders & Peterson 1996). Model implications are discussed in § 3.2.

2. If the disappearance of the blue peak in 1990–1994 is genuine, the radial velocity of the peak in the blue wing may have changed to $\approx 0^{+500}_{-1000}$ km s^{-1} in 1990, 1992, and 1994. In § 3.3 we discuss a possible model.

3. DISCUSSION

3.1. *Accretion Disk Line Emission*

The observed Hβ_{BC} profile as a whole is not consistent with the predictions of disk models at any epoch of observation. Nevertheless, if we wanted to interpret the secondary peak $\Delta v_r \approx -3000$ km s^{-1} as the Doppler-boosted peak of a disk contribution, we would need a disk with $r_{\mathrm{in}} \approx 600$, $r_{\mathrm{out}} \approx 1000$, $i \approx 21°$, following Chen & Halpern (1989). Nonconventional disk models (elliptical disks or warped disks; Eracleous et al. 1995; Marziani, Calvani, & Sulentic 1997) may be more successful in fitting the Hβ line profile at a given epoch. However, the variation observed between 1988 and 1990 and between 1995 and 1996 rules out the possibility of "switched-on" disk emission, since the Hβ_{BC} change appears to be restricted to the blue wing in both cases (see Fig. 1). The observed variation would require implausible changes of the disk parameters from one epoch to another.

3.2. *A Radially Moving Hβ_{BC} Line Component*

The moderate change in the Hβ_{BC} blue wing flux, $\approx$20%, without a simultaneous response in the red wing, points toward line emission from gas whose motion is predominantly radial. Given the observed blueshift and assuming optically thin clouds, as is generally believed to be the case for most Hβ-emitting clouds, the gas must be moving outward. We are not saying here that the Hβ_{BC} line emission is exclusively due to outflowing gas, but that a fraction related to the blue peak most probably is. Without further data, it is however not possible to elaborate on this result. Caution is needed, as the temporal sampling of our spectra is quite probably not sufficient to constrain line and continuum variations (Peterson 1993). The Hβ_{BC} line luminosity is $L(\mathrm{H}\beta_{\mathrm{BC}}) \approx 1.2 \times 10^{43}$ ergs s^{-1} for $\mathrm{H}_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$. Under the assumptions of the Menzel-Baker recombination theory, the light travel time across the BLR is $\tau_{\mathrm{LT}} \approx 107 L_{43}(\mathrm{H}\beta)^{1/3} n_{11}^{-2} f_{f,-5}^{-1}$ days, where L_{43} is the luminosity in units of 10^{43} ergs s^{-1}, n_{11} is the electron density in units of 10^{11} cm^{-3}, and $f_{f,-5}$ is the filling factor in units of 10^{-5}. Spectra obtained at a frequency of $\gtrsim 1$ month^{-1} are desirable. If the timescale for continuum variation is found to be comparable to τ_{LT}, then "ripples" in the line profile could be produced by reverberation effects.

At 20 cm, on a FIRST map (Becker, White, & Helfand 1994), PG 1512+370 appears as a double-lobed radio source, with lobes extending up to a projected linear distance of $\sim$400 kpc from the central core, at P.A. $\approx 105°$. Integral field spectroscopy revealed two [O III] $\lambda\lambda$4959, 5007–emitting regions approximately aligned along the east-west direction with the nucleus (Durret et al. 1994). Our 1996 spectrum also revealed the eastern emitting region as a "blob," at $\Delta v_r \approx -300$ km s^{-1}, in excellent agreement with the results of Durret et al. (1994). Extended [O III] $\lambda\lambda$4959, 5007–emitting regions in radio quasars show a statistical tendency to align with the radio-source axis in radio-loud, steep-spectrum quasars (Baum & Heckman 1989). Extended [O III] $\lambda\lambda$4959, 5007 provides some evidence in favor of outflowing gas related to the presence of radio ejecta (see the discussion for PG 1512+370 by Durret et al. 1994). We consider it unlikely that the blue peak is due to some outflowing gas that is episodically related to the radio jet. The dynamical timescale for the BLR is probably shorter than 8 yr; a blob moving at $v_r \gtrsim 3000$ km s^{-1} could not have maintained the same radial velocity over that time period.

3.3. *Binary BLR*

Within the errors in our spectra, the H$\beta_{\rm BC}$ profile variations can be ascribed to a stationary profile plus a superimposed component of variable radial velocity, contributing up to $\lesssim$10% of the total H$\beta_{\rm BC}$ line flux. In a binary BLR framework (see, e.g., Gaskell 1983; Gaskell 1996a, 1996b), we assume that the secondary component is observed at $v_r \sim 0$ km s^{-1} (in any case at $v_r \lesssim 1000$ km s^{-1}) between 1990 and 1994 (i.e., not clearly observed because it underlies the H$\beta_{\rm NC}$). This assumption is justified since the H$\beta_{\rm BC}$ underlying the H$\beta_{\rm NC}$ may be variable (Fig. 1), and a slightly redshifted "shoulder" partly underlying H$\beta_{\rm NC}$ may be identified in the 1996 (SPM) spectrum. The "shoulder" close to H$\beta_{\rm NC}$ was less prominent in 1995, when the blue wing was in turn much stronger. This interpretation is not fully satisfactory because the 1988 and 1996 Asiago spectra are of higher dispersion than the remaining spectra. The blue peak is resolved in the 1996 Asiago spectrum but not in the 1996 San Pedro Martir spectrum, because of the lower resolution (the two spectra were obtained 30 days apart). The same may be true for the 1990, 1992, and 1994 spectra.

If we accept the blue peak as a component of variable radial velocity, then the immediate implication for the orbit of a binary black hole system is that it is highly eccentric, and that the binary must have mass ratio very different from unity. From the observed-frame core-to-lobe flux ratio $R = 0.091$ measured on the FIRST map (1.4 GHz) we can estimate the angle between the line of sight and the radio axis. It is known that the relationship between R and orientation is valid in a statistical sense, probably because of a large intrinsic scatter in the Lorentz factor of the jet ($2 \lesssim \gamma \lesssim 20$; Padovani & Urry 1992; Ghisellini et al. 1993) and in the ratio f between the intrinsic jet luminosity and the unbeamed luminosity (Padovani & Urry 1992). We can write R as $R = f\delta^p$, where δ is the Doppler factor, and $p = 2.75$ for a continuous jet (Ghisellini et al. 1993). We assume $\gamma = 5$, and we use $f = 7 \times 10^{-3}$ (Padovani & Urry 1992), as appropriate for Fanaroff-Riley type II radio sources. We obtain an inclination $i \approx 21°$. For more extreme values of γ, namely, for $\gamma = 10$ and $\gamma = 2$, we obtain $i = 15°$ ($f = 7 \times 10^{-3}$) and $i = 26°$ ($f = 1 \times 10^{-2}$), respectively. To assume $i \approx 21°$ seems therefore reasonable. PG 1512+370 may have been excluded from superluminal motion searches, since its radio emission is lobe-dominated. However, at $i \approx 21°$ and $\gamma \approx 5$, we expect that PG 1512+370 should be superluminal with apparent transverse velocity $\beta_{\rm app} \approx 4$ (also if $\gamma = 2$, which implies $i = 26°$, we should observe $\beta_{\rm app} \approx 1.7$).

If $i = 21°$, an acceptable fit to the six observed radial velocities ($\chi^2_\nu \approx 1.76$), is obtained for binary period $P = 8.15$ yr, eccentricity $e \approx 0.75$, and semimajor axis $a = 1.6 \times 10^{16}$ cm. This solution corresponds to a total mass for the binary of $\approx 1.7 \times 10^7\ M_\odot$. The evolution of massive black hole binaries orbital parameters (semimajor axis, eccentricity) for several mass ratios has been studied recently by Quinlan (1996). From Figure 8 of his work we infer that $e \approx 0.75$ for $a = 1.6 \times 10^{16}$ cm is somewhat too large for any value of the initial eccentricity of the binary, save possibly for the case of initial eccentricity $e = 0.9$. In this case, PG 1512+370 should be in a very short-lived phase of the binary evolution: high eccentricity drives large gravitational radiation losses that should lead to the merging of the two black holes in $\sim 10^5$ yr. For the lower power Fanaroff-Riley type I radio source OJ 287 the case for a double black hole is stronger (e.g., Sillanpåå et al. 1996; Benitez et al. 1996), and rather similar orbital parameters are found: $e = 0.678 \pm 0.004$, $P = 12.07 \pm 0.01$ yr, $i = 4° \pm 2°$ (Lehto & Valtonen 1996). If the blazar nature of OJ 287 and the absence of obvious line emission is due to Doppler-boosted continuum emission, then PG 1512+370 and OJ 287 may both host a binary black hole whose orbital plane is observed at different inclination.

4. CONCLUSION AND OPEN ISSUES

We have presented evidence of moderate variations ($\lesssim$ 30% total line flux, with the largest variations occurring in the blue wing) in the H$\beta_{\rm BC}$ of PG 1512+370 from the analysis of spectra obtained from 1988 to 1996. A peak displaced by $\Delta v_r \approx -3000$ km s^{-1} with respect to the radial velocity of H$\beta_{\rm NC}$ (the "blue peak") has been observed in 1988 and 1996. We have attempted to interpret the observations according to a number of presently fashionable BLR models: accretion disk emission (§ 3.1); radially moving gas, and, in particular, emission due to gas trapped by the radio jet (§ 3.2); a binary BLR (§ 3.3). Only radially moving gas (but not occasionally associated with the radio jet) and a binary BLR are probably appropriate. This is one of the few cases where evidence from line profiles may support the presence of a binary BLR (with the cautionary note of § 3.3), although the eccentricity inferred from the observed radial velocity curve may be too high for the estimated major axis. Like OJ 287, PG 1512+370 would then be a very peculiar object observed in a very short-lived phase of its existence. However, we favor the idea that if H$\beta_{\rm BC}$ variations are the response to ionizing continuum changes, the presence of the blue peak and the observed variations of the H$\beta_{\rm BC}$ blue wing may be indicative of radial motion within the BLR. The blue peak may hence be a "ripple" produced by light echoes. Indeed, we expect that the blue peak will be detected by future observations at the same $\Delta v_r \approx -3000$ km s^{-1}, which therefore rules out the binary black hole model altogether (as in the case of 3C 390.3; Eracleous 1997; Eracleous et al. 1997). A set of high S/N spectra with a good temporal coverage is necessary in order to test the proposed hypotheses.

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