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# Is BL Lacertae an "orphan" AGN?

## Multiband and spectroscopic constraints on the parent population*

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**ABSTRACT**

*Aims.* We have analysed optical spectra of BL Lacertae, the prototype of its blazar subclass, to verify the broad H$\alpha$ emission line detected more than a decade ago and its possible flux variation. We used the spectroscopic information to investigate the question of the BL Lacertae parent population.

*Methods.* Low- and high-resolution optical spectra of BL Lacertae were acquired with the DOLORES spectrograph at the 3.58 m telescopio nazionale Galileo (TNG) during four nights in 2007–2008, when the source was in a relatively faint state. In three cases we were able to fit the complex H$\alpha$ spectral range with multiple line components and to measure both the broad H$\alpha$ and several narrow emission line fluxes.

*Results.* A critical comparison with previous results suggests that the broad H$\alpha$ flux has increased by about 50% in ten years. This might be due to an addition of gas in the broad line region (BLR), or to a strengthening of the disc luminosity, but such flux changes are not unusual in Broad Lined active nuclei. We estimated the BL Lacertae black hole mass by means of its relation with the bulge luminosity, finding $4{-}6 \times 10^8\ M_\odot$. The virial mass estimated from the spectroscopic data gives instead a value 20–30 times lower. An analysis of the disc and BLR properties in different AGNs suggests that this discrepancy is due to an underluminosity of the BL Lacertae BLR. Finally, we addressed the problem of the BL Lacertae parent population, comparing its isotropic quantities with those of other AGN classes. From the point of view of the narrow emission line spectrum, the source is located close to low-excitation radio galaxies. When one also considers its diffuse radio power, an association with FR I radio galaxies is severely questioned due to the lower radio luminosity (at a given line luminosity) of BL Lacertae. The narrow line and radio luminosities of BL Lacertae instead match those of a sample of miniature radio galaxies, which however do not show a BLR. Yet, if existing, "misaligned BL Lacertae" objects should have entered that sample. We also rule out the possibility that they were excluded because of a QSO optical appearance.

*Conclusions.* The observational constraints suggest that BL Lacertae is caught in a short term transient stage, which does not leave a detectable evolutionary "trace" in the AGN population. We present a scenario that can account for the observed properties.

**Key words.** galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual: BL Lacertae – galaxies: jets

## 1. Introduction

According to the commonly accepted scenario, the central engine of active galactic nuclei (AGNs) is a supermassive black hole (SMBH) fed by infall of matter from an accretion disc. Inner fast-moving clouds produce broad emission lines, which may be obscured by absorbing material, while outer clouds are responsible for narrow emission lines. About one fifth of AGNs is radio-loud (Kellermann et al. 1994), showing plasma jets sometimes extending on Mpc scales. Among them, BL Lac objects and flat spectrum radio quasars (FSRQs) form the blazar class, characterized by variable emission from the radio to the $\gamma$-ray band, with flux variations on time scales from hours to years, high radio and optical polarization, core-dominated radio morphology, flat radio spectra, and apparent superluminal motion of radio jet components. Their properties are explained in terms of plasma relativistic motion in a jet pointing at a small angle with the line of sight, with consequent beaming of the observed radiation (Blandford & Rees 1978). Hence, the continuum radiation of blazars is dominated by the relativistically beamed non-thermal radiation from the jet.

In FSRQs, thermal emission from the disc may be observable in the optical-ultraviolet band when the source is not in a flaring state. Disc signatures were detected e.g. in 3C 273 (Smith et al. 1993; von Montigny et al. 1997; Grandi & Palumbo 2004; Türler et al. 2006), 3C 279 (Pian et al. 1999), PKS 1510-089 (Kataoka et al. 2008; D'Ammando et al. 2009), 3C 345 (Bregman et al. 1986), and 3C 454.3 (Raiteri et al. 2007b, 2008). Moreover, strong broad and narrow emission lines are usually present in their spectra.

As for BL Lac objects, according to the original definition, they may show at most weak emission lines, with equivalent widths not exceeding 5 Å in the rest frame (Stickel et al. 1991). This seems to be due not so much to low line fluxes, but rather to a high continuum flux (Scarpa & Falomo 1997). Indeed, strong emission lines, in particular broad ones, have occasionally been detected in the spectra of BL Lac objects in faint states. These include BL Lacertae, the prototype of the blazar subclass named

* Based on observations made with the Italian Telescopio Nazionale Galileo operated on the island of La Palma by the Centro Galileo Galilei of INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque del los Muchachos of the Instituto de Astrofisica de Canarias.

after it (Vermeulen et al. 1995; Corbett et al. 1996, 2000), and the distant source AO 0235+164 (Cohen et al. 1987; Nilsson et al. 1996; Raiteri et al. 2007a).

The unified scheme for radio-loud AGNs predicts that BL Lac objects and FSRQs are the beamed counterparts of Fanaroff-Riley type I (FR I) and Fanaroff-Riley type II (FR II) radio galaxies, respectively, even if these correspondences were questioned by various observing evidences (e.g. Tadhunter 2008). In particular, many BL Lac objects show high, FR II-like extended radio powers and morphologies (see e.g. Landt & Bignall 2008, and references therein). The distinction between blazars and radio galaxies, as well as that between FSRQs and BL Lac objects, has been discussed by several authors, and different criteria have been proposed, involving the value of the Ca H&K break (Marcha et al. 1996), or the strength of the oxygen-narrow emission-lines (Landt et al. 2004).

A powerful way to classify AGNs is their position in diagnostic diagrams comparing selected emission line ratios (Heckman 1980; Baldwin et al. 1981). In particular, ratios of lines close in wavelength, like [O III]/H$\beta$, [N II]$\lambda$6583/H$\alpha$, [S II]$\lambda\lambda$6716, 6731/H$\alpha$, and [O I]/H$\alpha$ are expected to be the most reliable ones (Veilleux & Osterbrock 1987). The application of diagnostic diagrams to radio-loud galaxies by Laing et al. (1994) confirmed former suggestions that FR II sources can be divided between high-excitation galaxies (HEG) and low-excitation galaxies (LEG). In particular, Buttiglione et al. (2010) verified this dichotomy when analysing the radio sources belonging to the well known 3CR catalogue. They found prominent broad lines in a sub-sample of HEG, but not in LEG. Moreover, they saw that HEG are associated with very powerful FR II only, while LEG are spread on a wide range of radio powers, and can be of both FR II and FR I type. Actually, the situation is even more complex, as the existence of miniature radio galaxies, characterized by extremely low radio power, relatively luminous narrow emission lines, and no BLR, demonstrates (Baldi & Capetti 2009).

An analysis of the spectroscopic properties of blazars to understand their relationship with the radio galaxies (and other AGN classes) is not an easy task, because the dramatic variability of the non-thermal continuum flux strongly affects the appearance of lines, especially in BL Lac objects. However, this analysis can help clarify whether blazars differ from radio galaxies only for their orientation with respect to the line of sight, or if they are intrinsically different sources.

We present spectroscopic observations of BL Lacertae carried out in 2007–2008 with the 3.58 m telescopio nazionale Galileo (TNG) on the Canary Islands, to address the problem of its parent population. In the same period BL Lacertae was the target of a multiwavelength campaign by the Whole Earth Blazar Telescope[1] (WEBT), also involving three pointings by the XMM-Newton satellite. The results of the WEBT campaign have been presented by Raiteri et al. (2009). The source was observed in a relatively faint state at all wavelengths, and a UV excess was clearly visible in the source spectral energy distribution (SED), which was interpreted as the signature of thermal radiation from the accretion disc.

## 2. Spectroscopic observations and data reduction

All spectra were taken with the telescopio nazionale Galileo (TNG), a 3.58 m optical/infrared telescope located on the Roque de los Muchachos in La Palma Canary Island (Spain).

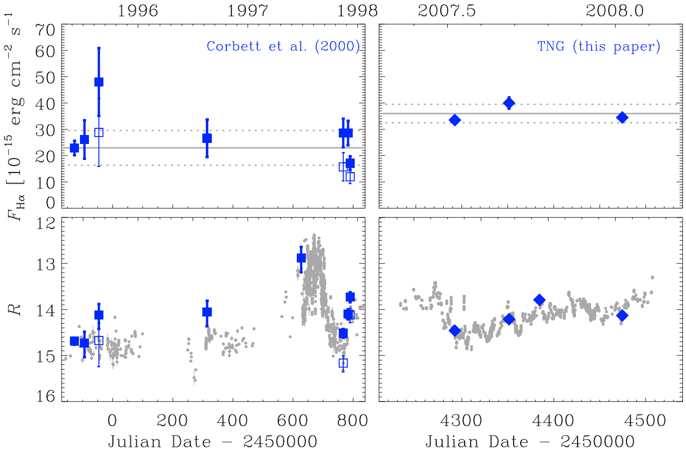


**Fig. 1.** The behaviour of the H$\alpha$ broad emission line flux as a function of time (*top panels*) compared to the continuum flux evolution (*bottom panels*, *R*-band magnitudes) in 1995–1997 (*left*) and 2007–2008 (*right*). Blue filled squares display the results of Corbett et al. (2000); blue empty squares represent data with revised flux calibration; blue diamonds show the results obtained in this paper by analysing the TNG data. Grey dots represent data from the WEBT collaboration (Villata et al. 2004; Raiteri et al. 2009). The solid horizontal lines in the upper panels indicate the average H$\alpha$ flux in the corresponding period, while dotted lines are drawn through one standard deviation from the mean value.

The observations were made with the DOLORES (Device Optimized for the LOw RESolution) spectrograph installed at the Nasmyth B focus of the telescope. The detector was a 2048 × 2048 pixels E2V 4240 back-illuminated CCD, with a pixel size of 13.5 $\mu$m, and a scale of 0.252″ pixel$^{-1}$, which implies a field of view of 8.6′ × 8.6′.

The spectroscopic observations were performed in service mode on 2007 July 10–11, September 7, and October 10, and on 2008 January 8, during a multiwavelength campaign by the WEBT; in particular, the first and last observations were contemporaneous to XMM-Newton pointings at the source (Raiteri et al. 2009). Figure 1 (bottom right) shows the *R*-band light curve obtained by the 30 optical telescopes of the WEBT: the source showed a noticeable variability, with short-term (intra-day or inter-day) flickering superposed on a longer-term trend. Blue diamonds display the results of aperture photometry performed on TNG images acquired with the Cousins' *R* filter just before/after the spectra, with the same prescriptions used to derive the WEBT magnitudes, i.e. an aperture radius of 8″, and background derived from a surrounding annulus with 10″ and 16″ radii. In this way, Villata et al. (2002) estimated that the measured flux density includes 60% of the host galaxy flux. Table 1 reports the *R*-band magnitudes[2] derived from the TNG imaging frames according to the above WEBT prescriptions. Figure 1 shows that the photometry on the TNG images agrees excellently with the WEBT data and helps to put the spectroscopic observations into context.

These were performed with a 2″-width long-slit, which was aligned along the parallactic angle to minimize light losses due to atmospheric dispersion. For each observing epoch, we obtained both low-resolution spectra with the LR-B grism, covering the wavelength range 3500–7700 Å with dispersion 2.52 Å pixels$^{-1}$ and resolution 1200 (for a 2″ slit), and high-resolution spectra with the VHR-R grism, sensitive to

[1] http://www.oato.inaf.it/blazars/webt/

[2] Throughout the paper we report uncertainties at 1$\sigma$ confidence level.

**Table 1.** Results of aperture photometry on the TNG imaging frames.

| Date | $R^{a}$ [mag] | ${F_{\rm R}}^{b}$ [$10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$] |
|---|---|---|
| 2007 Jul. 10–11 | 14.46 ± 0.01 | 3.16 ± 0.01 |
| 2007 Sep. 7 | 14.21 ± 0.02 | 4.12 ± 0.09 |
| 2007 Oct. 10 | 13.79 ± 0.01 | 6.31 ± 0.05 |
| 2008 Jan. 8 | 14.13 ± 0.03 | 4.42 ± 0.11 |

**Notes.** [(a)] *R*-band magnitudes obtained from photometry with 8″ aperture radius; [(b)] flux densities at 6410 Å derived from photometry with 2″ aperture radius, used to normalise the spectra.

wavelengths from 6100 to 7700 Å with dispersion 0.70 Å pixels$^{-1}$ and resolution 5000. For each grism, two consecutive frames were taken and subsequently combined, for a total exposure of 600 s in LR-B, and 1400 s in VHR-R. The resulting signal-to-noise ratios of the co-added spectra are ∼50–100 and ∼100–200 for the low- and high-resolution spectra respectively.

The use of both LR-B and VHR-R grisms allowed us to cover the spectral range where the most relevant emission lines of the optical spectrum are expected, in particular the key diagnostic lines H$\beta$, [O III]$\lambda\lambda$4959, 5007, [O I]$\lambda\lambda$6300, 64, H$\alpha$, [N II]$\lambda\lambda$6548, 84, and [S II]$\lambda\lambda$6716, 31. The high-resolution spectra were needed to disentangle H$\alpha$ from the [N II] doublet.

The `longslit` package of the NOAO's Image Reduction and Analysis Facility (IRAF)[3] was used to perform bias-subtraction, flat-field correction, wavelength calibration, background subtraction, spectra extraction (performed over 2″ in the spatial direction), and flux calibration. For the last task we used the spectrophotometric standard star BD +28°4211 (Oke 1990). We discarded the October spectra because of their low quality.

The absolute flux calibration of the spectra was checked through synthetic aperture photometry on the images taken in the Cousins' *R* band just before/after the spectra. By setting an aperture size of 2″, we derived the flux densities at $\lambda_{\rm eff}$ = 6410 Å reported in Table 1. The comparison with the spectra continuum around 6400 Å revealed that all spectra flux densities were in fair agreement with the fluxes inferred from photometry, with the only exception of the VHR-R spectra of July 2007. Indeed, the scaling factors to apply to the LR-B spectra were: 0.96, 0.95, 1.03 for July 2007, September 2007, and January 2008, respectively, while for the VHR-R spectra we obtained: 1.27, 0.99, and 1.02. For the LR-B spectra, which extend over almost all the wavelength range covered by the broad-band *R* filter, these calibration factors were checked by convolving the BL Lacertae spectra with the transmission curve of the TNG *R*-band filter, multiplied by the CCD quantum efficiency curve. We verified that the uncertainty on the calibration factors is of the order of 2%.

By following Scarpa et al. (2000), who gave the host galaxy brightness $R$ = 15.55 ± 0.02 and its effective radius $r_{\rm e}$ = 4.8″, and adopting a De Vaucouleur brightness profile, we estimated that within 2″ the host galaxy contribution is ∼$0.32\times10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, i.e. ∼10% of the observed flux in July, and ∼8% and ∼7% in September and January, respectively. This result is confirmed by the analysis of the Ca H&K break strength in the spectra. In the January spectrum we found that the ratio between the fluxes in the rest-frame wavelength ranges 4000–4100 Å and 3850–3950 Å is $D_n(4000)$ ∼ 1.06 (Balogh et al. 1999). Assuming $D_n(4000)$ ∼ 2 for the host galaxy (Kauffmann et al. 2003), as typical of giant early-type galaxies, this implies a host galaxy contribution not greater than a few percent. Thus we did not correct the spectra for the host galaxy contribution, because it is negligible for our purposes.

The VHR-R spectra were corrected for the telluric absorption bands, a particularly important step, because the 6870 Å oxygen *B*-band affects the blue wing of the H$\alpha$ line. This was done by dividing the spectra by a template obtained from the spectrophotometric standard star.

Figure 2 displays the low-resolution (left panels) as well as the high-resolution (right panels) spectra, the latter both before and after correction for atmospheric absorption around the H$\alpha$ line.

We measured the emission line intensities by means of the `specfit` package in IRAF (Kriss 1994). To reduce the number of free parameters we fixed the relative wavelength distance between lines and required the *FWHM* to be the same for all the narrow lines. From the low-resolution spectra we derived the [O III]$\lambda\lambda$4959, 5007 flux, and an upper limit to the H$\beta$ flux. In the high-resolution spectra, we fitted the 6700–7350 Å spectral region with seven components: a Gaussian profile for each of the lines: H$\alpha$ (broad and narrow), [N II]$\lambda\lambda$6548, 84, and [S II]$\lambda\lambda$6716, 31, plus a linear component for the continuum. The results of this spectral fitting are shown in Fig. 3. The fit to the [S II]$\lambda\lambda$6716, 6731 doublet must be considered with caution, because this line is strongly affected by atmospheric absorption and thus its measurement strongly depends on the telluric correction (see Fig. 2). The *FWHM* of the narrow lines ranges from ∼500 to ∼600 km s$^{-1}$, while that of the broad H$\alpha$ component is 4200–5000 km s$^{-1}$. Including a further component to fit the [O I]$\lambda\lambda$6300, 64 line resulted in a marginal detection only.

Table 2 reports the line fluxes after correction for the Galactic extinction, adopting $A_B$ = 1.42, $E(B-V)$ = 0.35, and the extinction law of Cardelli et al. (1989).

## 3. Discussion

### 3.1. Variability of the broad H$\alpha$ emission line

The first detection of broad emission lines in the optical spectrum of BL Lacertae was reported by Vermeulen et al. (1995). They took two spectra in May and June 1995, and measured H$\alpha$ with *FWHM* of 3400–3700 km s$^{-1}$ and flux of $4.4\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$, while for H$\beta$ they obtained *FWHM* = 4400 km s$^{-1}$ and $F$ = $1.3\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$. They stressed that such a luminous H$\alpha$ line should have been observed before, while it is not recognizable in earlier spectra taken in 1975–1976 by Miller & Hawley (1977), in 1985 by Lawrence et al. (1996), and in 1989 by Stickel et al. (1993). They estimated that the broad H$\alpha$ flux may have increased by at least a factor 5 since 1989.

Soon after, Corbett et al. (1996) analysed two other optical spectra acquired in June 1995, and confirmed the results of Vermeulen et al. (1995). They discussed the appearance of the H$\alpha$ line as due to an increase of either the amount of gas in the broad line region (BLR) or the strength of the photoionising source. In the latter case, the accretion disc seemed the most likely source of photoionising radiation. The signature of the accretion disc was later recognized by Raiteri et al. (2009) as a UV excess in the broad-band SEDs of BL Lacertae built with contemporaneous low-energy data from the WEBT and high-energy data from the XMM-Newton satellite.

[3] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

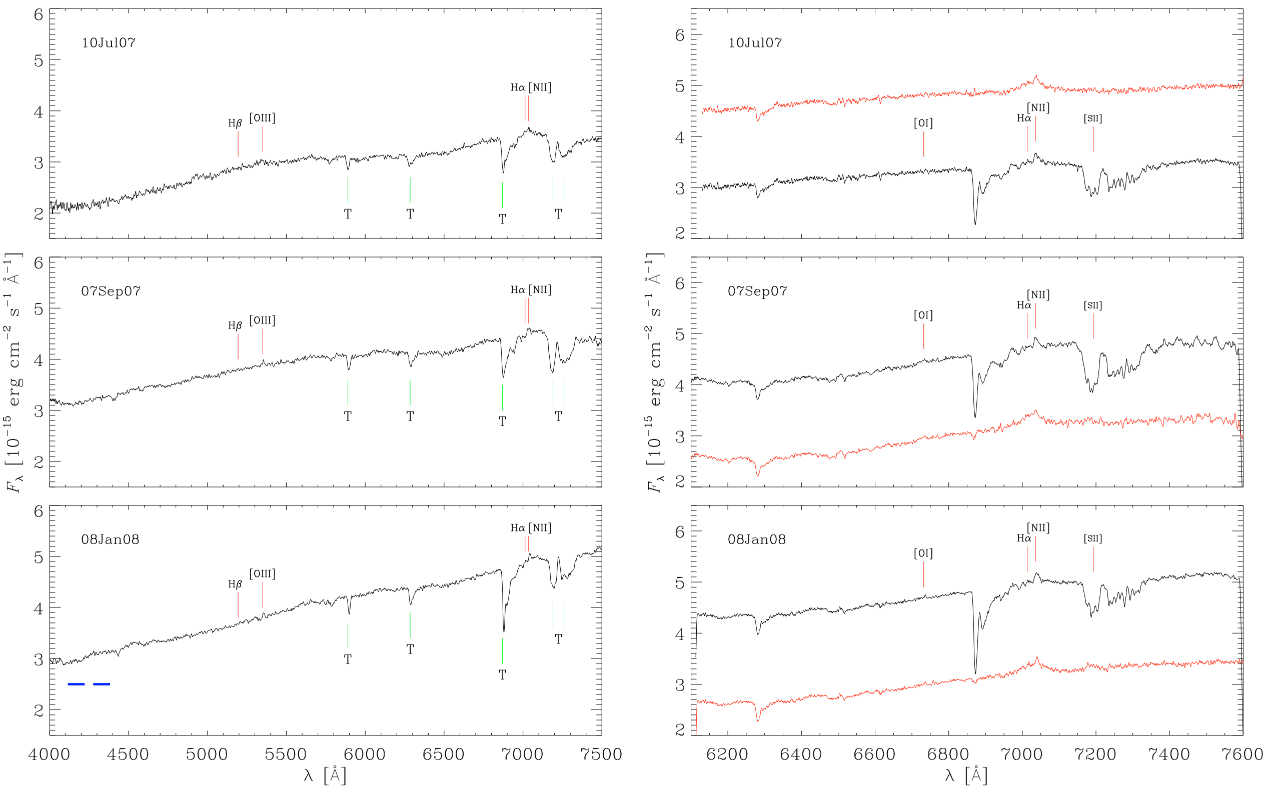


**Fig. 2.** *Left panels*: low-resolution TNG spectra. The position of the emission lines is indicated as well as that of the telluric absorption lines. Blue horizontal lines in the bottom panel mark the wavelength intervals used to calculate the $D_n(4000)$ spectral index defining the strength of the Ca H&K break. *Right panels*: high-resolution TNG spectra both before (black) and after (red) correction for the telluric absorption lines around the H$\alpha$ line. The corrected spectra are shifted in flux for sake of clarity.

**Table 2.** Emission lines fluxes after correction for Galactic extinction. All fluxes are $10^{-15}$ erg cm$^{-2}$ s$^{-1}$; *FWHM* are km s$^{-1}$.

| Obs. | H$\beta$ | [O III]$\lambda$4959, 5007 | H$\alpha$(narrow) | [N II]$\lambda$6548, 84 | [S II]$\lambda\lambda$6716, 6731 | H$\alpha$(broad) | *FWHM* |
|---|---|---|---|---|---|---|---|
| 2007 Jul. 10–11 | <7.6 | 4.7 ± 1.2 | 2.4 ± 0.5 | 5.3 ± 0.6 | <3.1 | 33.5 ± 0.9 | 4600 |
| 2007 Sep. 7 | <3.0 | 3.4 ± 0.5 | 4.8 ± 1.5 | 6.1 ± 1.0 | 3.9 ± 0.9 | 40.0 ± 2.1 | 5000 |
| 2008 Jan. 8 | <2.0 | 2.5 ± 0.4 | 2.5 ± 0.6 | 4.7 ± 0.7 | 4.4 ± 0.8 | 34.5 ± 0.9 | 4200 |

The spectroscopic monitoring of BL Lacertae was continued by Corbett et al. (2000), with eight spectra taken between June 1995 and December 1997, in seven of which they were able to measure the H$\alpha$ broad emission line. Their results are reported in Fig. 1, where the upper left panel shows their line flux (corrected for extinction and host galaxy contamination) as a function of time, while the lower left panel displays their continuum estimates superposed to the light curve by the WEBT collaboration (Villata et al. 2004). They could not distinguish the H$\alpha$ line in June 1997, when the source was experiencing a big optical outburst. When considering their estimates of the H$\alpha$ broad emission line flux together with ours, we find an average flux of $30.6 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, and a standard deviation of $8.8 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. This would imply that if we take into account the errors, all H$\alpha$ fluxes are within one standard deviation from the mean value, with the only exception of the December 1997 value. Indeed, Corbett et al. (2000) concluded that in 1995–1997 there was no "compelling evidence" of "any significant variation", and now we could add that after about 10 years the H$\alpha$ flux has still roughly the same intensity.

However, the WEBT photometry allows us to improve the Corbett et al. (2000) absolute flux calibration. The spectra of August 24, 1995, November 14, 1997, and December 7, 1997 are the ones for which we both have contemporaneous WEBT data and found significant deviations of the Corbett et al. (2000) measures from the WEBT ones. The blue empty squares in Fig. 1 represent data rescaled; the flux rescaling factors are 0.6, 0.55, and 0.7 for the three spectra, respectively. Thus, if we consider all the H$\alpha$ broad emission line fluxes in the 1995–1997 period, rescaled to match photometric values, we find an average value of $(23.0 \pm 6.6) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. This can be compared to the average value of $(36.0 \pm 3.5) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ obtained by considering our three measurements in 2007–2008, suggesting that a ~50% increase of the broad H$\alpha$ intensity may have occurred in a roughly 10 year time interval. However, this is not unusual and it is not necessarily due to an evolutionary trend. Indeed, oscillations of the H$\alpha$ flux up to ~77% on a time scale of a few years have been reported by Kaspi et al. (2000) for PG quasars.

Due to its greater distance from the central engine, the narrow line region (NLR) is expected to react to variations of the disc luminosity on much longer timescales than those characterizing the BLR. Indeed Corbett et al. (1996) reported fluxes of the narrow H$\alpha$ line component and of [N II] that are inside the range of our results (see Table 2). They also identified [O I] and [Fe VII]. Vermeulen et al. (1995) measured the narrow [O III] and [N II] emission lines, with fluxes similar to ours. [O III] was previously measured also by Stickel et al. (1993) in 1989, and

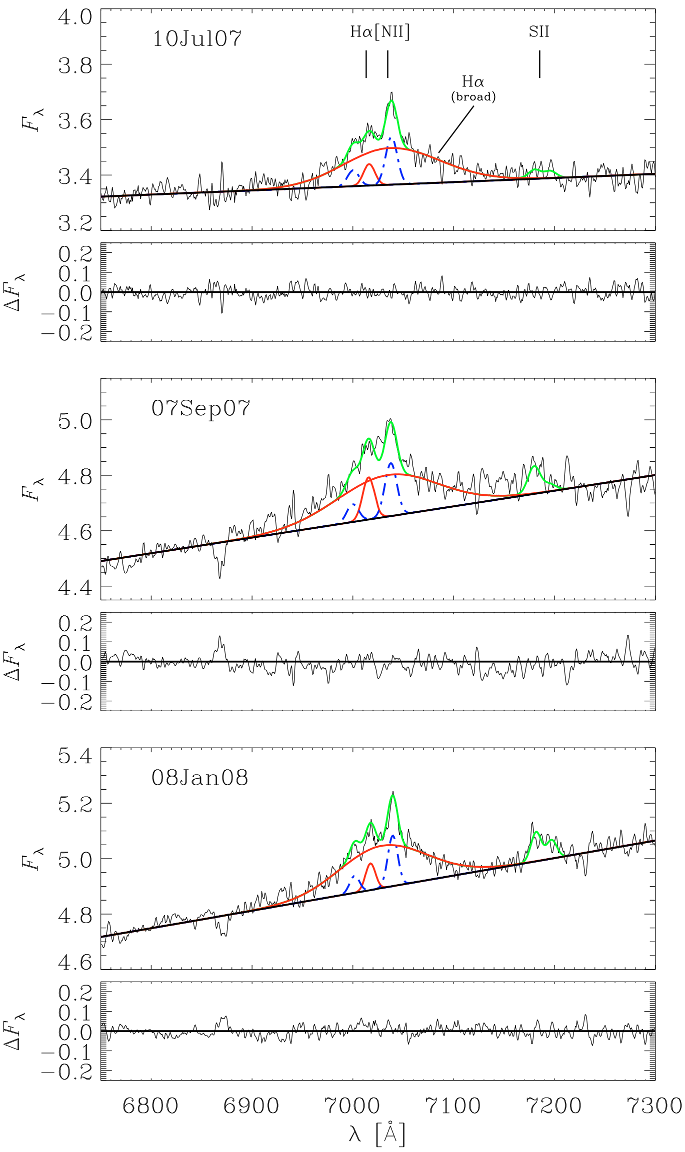


**Fig. 3.** *Top panels*: enlargement of the high-resolution, telluric-corrected spectra of Fig. 2, showing the results of the spectral fitting: red continuous lines indicate the fit to the broad and narrow components of the H$\alpha$ line; blue dotted-dashed lines show the fit to the [N II] doublet; the green line displays the overall fit, which includes a tentative fit to the [S II] line. *Bottom panels*: residuals of the spectral fit. Fluxes and residuals are given in $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ units.

by Lawrence et al. (1996) in 1985, who estimated a flux within a factor of 2 with respect to our spectra. In conclusion the NLR luminosity did not undergo significant changes in the last twenty years, although it must be noted that the narrow line fluxes are known with larger uncertainties than the broad H$\alpha$.

### *3.2. Black hole mass, BLR, and accretion disc properties*

The masses of SMBH powering AGNs can be estimated in a number of different ways.

One method relies on the presence of a relation between SMBH mass and near-infrared bulge luminosity as derived by Marconi & Hunt (2003). From the BL Lacertae host galaxy brightness $R = 15.55 \pm 0.02$ (Scarpa et al. 2000), correcting for Galactic extinction and using a mean colour index for elliptical galaxies of $R - K = 2.71$ (Mannucci et al. 2001) we obtain an apparent magnitude $K = 11.95$. This translates into an absolute magnitude $M_K = -25.33$, and hence $\log(L_K/L_{\odot,K}) = 11.44$. According to Marconi & Hunt (2003), this value implies $M_{\rm BH} \sim 6 \times 10^8\ M_\odot$.

A revision of the SMBH mass versus bulge luminosity relation for AGNs has been proposed by Bentz et al. (2009b), using a sample of 26 objects observed by the Hubble Space Telescope, and for which SMBH masses have been estimated through the reverberation-mapping technique. By adopting for BL Lacertae $L_{\rm V} = 5.55 \times 10^{10}\ L_\odot$ we derive $M_{\rm BH} = 3.76^{+1.28}_{-0.95} \times 10^8\ M_\odot$, in substantial agreement with the previous estimate[4].

Another possible approach is to use the spectroscopic information, and to calculate the virial mass: $M_{\rm BH} = f R_{\rm BLR} \sigma^2_{\rm line}/G$, where $f$ is a factor depending on the BLR structure, kinematics, and orientation; $R_{\rm BLR}$ is the size of the BLR; $\sigma_{\rm line}$ is the line dispersion, and $G$ is the gravitational constant. Following Peterson et al. (2004), $f = 5.5$, and $\sigma_{\rm line} = FWHM/2.355$. Lacking a measurement from reverberation mapping, the size of the BLR can be derived from the scaling relationship with its luminosity as discussed by Kaspi et al. (2005). According to our data, the luminosity of the broad H$\alpha$ line is $\sim 4 \times 10^{41}$ erg s$^{-1}$; adopting a flux ratio H$\alpha$/H$\beta$ $\sim$ 3 (an assumption supported by the measurements by Vermeulen et al. 1995), this leads to $R_{\rm BLR} \sim 5$ lt day. Taking $FWHM = 4600$ km s$^{-1}$ from Table 2, we obtain $M_{\rm BH} \sim 2 \times 10^7\ M_\odot$. Following the prescription of Marconi et al. (2008) to account for the possible role of radiation pressure on the BLR, we derive a relatively small correction term to the black hole mass of $\sim 0.6 \times 10^7\ M_\odot$. The virial estimate of $M_{\rm BH}$ is then about 20–30 times lower than the values derived above.

At this stage the reason for the discrepancy is unclear.

Further clues on the properties of BL Lacertae come from the relationship of the observed BLR with the accretion disc. The Optical Monitor XMM-Newton observations of BL Lacertae presented in Raiteri et al. (2009) revealed a sharp up-turn in the SED ultraviolet region, the characteristic signature of the Big Blue Bump associated with the emission of the accretion disc. From Figs. 6 and 7 in Raiteri et al. (2009) one can estimate a disc luminosity at 2500 Å of $\log L_\nu(2500\ \text{Å}) \sim 29.4$ erg s$^{-1}$ Hz$^{-1}$. This value is similar to that measured in type 1 AGN (both radio-loud and radio-quiet) like Fairall 9, PG 1229+204, 3C 390.3, 3C 120, Mkn 509, PG 2130+099, PG 0844+349, and Akn 120 (Vasudevan & Fabian 2009). The luminosity of the broad H$\beta$ lines of these sources ranges from 0.2 to $0.6 \times 10^{43}$ erg s$^{-1}$ (Kaspi et al. 2005). For BL Lacertae, considering its broad H$\alpha$ line luminosity and the H$\alpha$/H$\beta$ flux ratio (see above), we obtain a factor of ~15–40 lower.

A comparison with broad-line radio galaxies in the 3CR sample (Buttiglione et al. 2010) gives a similar result: the ratio between the broad H$\alpha$ and the rest-frame UV flux ranges between 100 and 250 Å, while this ratio for BL Lacertae is ~0.3 Å. This difference is preserved considering an AGN of very low BLR luminosity, ~100 smaller than BL Lacertae, the LINER galaxy NGC 4579 (Barth et al. 1996, 2001), for which this value is ~275 Å. Apparently, the BLR of BL Lacertae is strongly underluminous with respect to its disc emission when compared to other AGN.

This suggests a possible interpretation for the different values of SMBH mass found above. In fact, $M_{\rm BH}$ scales with the

[4] The SMBH mass of BL Lacertae was also calculated by Woo & Urry (2002) through the correlation between the SMBH mass and the stellar velocity dispersion $\sigma$; the estimate of $\sigma$ is inferred from the morphological parameters of the host galaxy, via the fundamental plane (Jorgensen et al. 1996). They found $M_{\rm BH} = 1.70 \times 10^8\ M_\odot$.

BLR luminosity as $M_{\rm BH} \propto L_{\rm BLR}^{0.6-0.7}$. To account for an underestimate of the SMBH mass by a factor of 20–30, the BLR should be underluminous by a factor of 70–300, in broad agreement to what we derived considering the ratio between BLR and UV fluxes.

### 3.3. The parent population

We here explore how BL Lacertae would look like when seen with its jet pointing at a larger angle from our line of sight, i.e. what extragalactic sources might represent the misoriented parent population. We thus consider all quantities that are not affected by beaming and that might eventually depend on orientation only if there is selective obscuration, as e.g. due to a flattened circumnuclear dust structure, e.g. a torus.

The host of BL Lacertae is a giant elliptical galaxy of absolute magnitude $M_K = -25.33$ (see Sect. 3.2), nearly two magnitudes brighter than the characteristic absolute magnitude $M^*$ in this band (Schechter 1976; Huang et al. 2003). The emission from the accretion disc, to which we associate the emission in the near *UV* band at 2500 Å, amounts to $10^{29.4}$ erg s$^{-1}$ Hz$^{-1}$. In order to estimate the contrast between the disc and the host we used the Raiteri et al. (2009) black-body fit to the accretion disc emission, which gives an *R*-band flux of $0.95 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ The host-galaxy observed magnitude $R = 15.55$ (Scarpa et al. 2000), after correcting for Galactic extinction, translates into a flux of $3.07 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. This implies a ratio between host and nucleus of ~3, similar to that measured in Seyfert 1 and Broad Line radio galaxies (Bentz et al. 2009a).

The extended radio emission is also unaffected by orientation. By means of VLA maps at 20 cm, Antonucci & Ulvestad (1985) estimated an extended radio flux of 40 mJy. More recent VLA observations at 20 cm for the MOJAVE project (Cooper et al. 2007) resulted in an extended flux of 18 mJy, essentially confirming the earlier results. These high spatial resolution observations might, in principle, have missed diffuse low-surface brightness, steep-spectrum emission. We then consider the 74 MHz flux density measured for BL Lacertae in the VLA Low-frequency Sky Survey (VLSS, Cohen et al. 2007), i.e. $F_{74} = 1.46$ Jy. Even in the assumption that the radio core does not contribute significantly at this low frequency, this translates into an upper limit of ~180 mJy at 1400 MHz (having adopted a radio spectral index of 0.7). This is an extremely conservative limit, considering that its radio core has a typical flux of ~2 Jy (see e.g. Kharb et al. 2010). Thus we are confident that a value of 40 mJy at 1400 MHz is well representative of the total extended emission in BL Lacertae. This corresponds to a radio luminosity power of $\log P_{\rm ext} = 30.57$ erg s$^{-1}$ Hz$^{-1}$.

From the point of view of the emission lines, we derived a broad H$\alpha$ luminosity of $\sim 4 \times 10^{41}$ erg s$^{-1}$ (see Sect. 3.2). Considering the narrow emission lines, from Table 2 we estimate a [O III] luminosity of $\sim 4 \times 10^{40}$ erg s$^{-1}$. The narrow emission line ratios can contribute to characterize the properties of an AGN, but unfortunately accurate measurements from our data are available only for [O III] and [N II][5]. As discussed in Sect. 3.1, the narrow emission lines do not seem to have varied significantly in the last 20 years, so we can complement our data with those from the literature. However, the spectrum of Vermeulen et al. (1995) does not improve the situation,

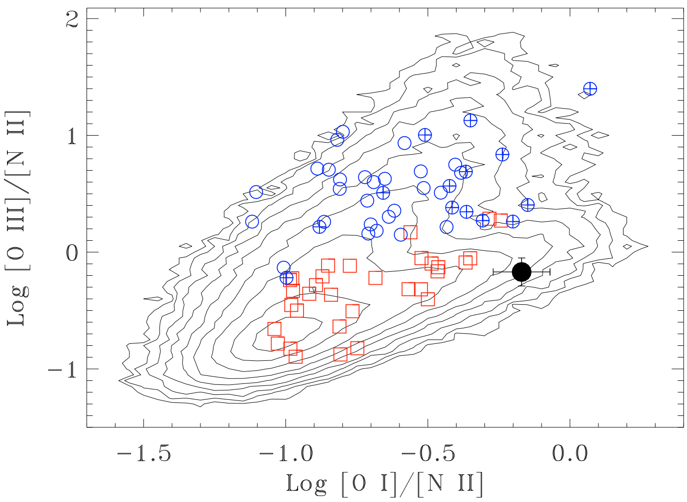


**Fig. 4.** The diagnostic index log[O III]/[N II] vs. log[O I]/[N II] of BL Lacertae derived from our TNG data and those of Corbett et al. (1996) (black dot). The red squares and blue circles show the distribution of LEG and HEG, respectively, according to the results by Buttiglione et al. (2010). The crossed circles mark HEG that also show a BLR. Contours represent the density of SDSS emission line galaxies from Kewley et al. (2006).

because the H$\beta$ line is detected, but a decomposition into narrow and broad component could not be performed. The observations by Corbett et al. (1996) cover only the red part of the spectrum ($\lambda \gtrsim 6000$ Å) where they saw a rather well-defined [O I]$\lambda$6300 line. This enables us to locate BL Lacertae in a non-standard diagnostic plane defined by the ratios [O I]/[N II] and [O III]/[N II] (Fig. 4). As a comparison, we show in this diagram the location of the 3CR sources (limited to a redshift of 0.3) from Buttiglione et al. (2010). The two main spectroscopic classes of Low and High Excitation Galaxies (LEG and HEG, respectively) define two separate sequences, which are also present in the SDSS emission line galaxies from Kewley et al. (2006). BL Lacertae falls in a region not well populated by 3CR sources, but it is closer to LEG than to HEG; furthermore it lies on the branch of the LINERs from the SDSS. This suggests a tentative identification as a Low Excitation Galaxy from the point of view of its narrow emission line spectrum.

Which class of objects share the properties of BL Lacertae described above? Let us start considering the radio-galaxies in the 3CR sample, see Fig. 5. The extended radio luminosity of BL Lacertae is at the faint end of the FR I in the 3CR, with only the nearby source 3C 272.1 (M 84) being fainter. From the point of view of the narrow emission lines, the [O III] luminosity of BL Lacertae lies instead at the high end of 3CR/FR I. Thus this source is a strong outlier (by a factor of ~200–400 depending on the adopted value for its radio luminosity) from the relationship between line and radio luminosities followed by 3CR radio-galaxies[6]. This is true not only considering FR I, but also from a comparison of the LEG and HEG classes, and casts substantial doubts on the association of BL Lacertae with FR I, but more in general with the radio-galaxies in the 3CR sample. Note that also other classical samples of radio galaxies, like the B2 and

[5] The narrow component of H$\alpha$ is heavily blended with the brighter broad emission; the [S II] doublet is significantly uncertain as it falls deep into a telluric band; our data provide us with an upper limit on H$\beta$ and only with a tentative detection of [O I]$\lambda$6300.

[6] Other two strong outliers from the line-radio correlation are present in the 3CR, namely 3C 371 and 3C 084; intriguingly, 3C 371 is a well-known BL Lac, while 3C 084 (although often classified differently) hosts a highly polarized and variable optical nucleus (Martin et al. 1976), typical of BL Lac objects.

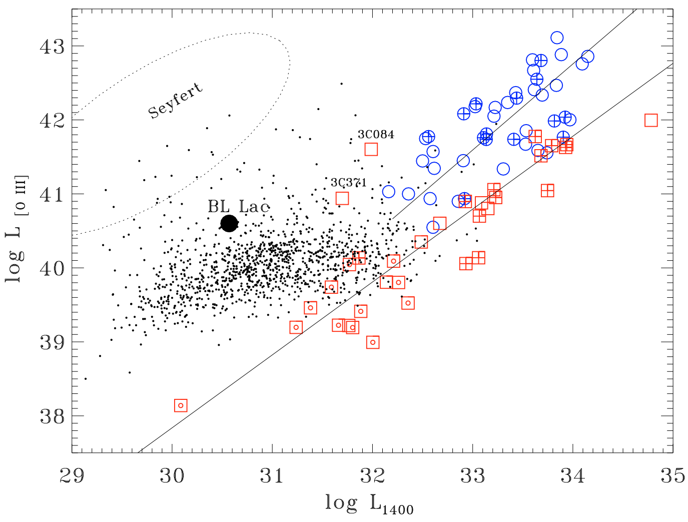


**Fig. 5.** [O III] luminosity [erg s$^{-1}$] as a function of radio luminosity at 1400 MHz [erg s$^{-1}$ Hz$^{-1}$]. The large black dot represents the location of BL Lacertae. Blue circles are HEG (crossed circles are broad line objects), while red squares are LEG. When possible, we further mark LEG according to their FR type: crossed squares are FR II/LEG and dotted squares are FR I/LEG. The two solid lines represent the best linear fit obtained for the HEG and LEG sub-populations separately. The small black dots are the radio-sources from the SDSS/NVSS sample (see text for details). The dotted ellipse includes the Seyfert galaxies considered by Whittle (1985).

the 2 Jy (Morganti et al. 1997; Tadhunter et al. 1998) follow relations between radio and line emission similar to the 3CR.

Baldi & Capetti (2009) showed that a large ratio of line emission to the radio power with respect to 3CR sources is characteristic of the radio-loud AGN selected by Best et al. (2005). The latter authors cross-matched the ~212 000 galaxies drawn from the SDSS-DR2 with the NVSS and FIRST[7] radio surveys, selecting a sample of 2215 radio-loud AGN (with a radio flux threshold of 5 mJy) to which we refer hereafter as the SDSS/NVSS sample. Baldi & Capetti (2010) explored the spectro-photometric properties of the SDSS/NVSS objects showing that they are generally hosted by massive early-type galaxies with a low excitation emission line spectrum. From the point of view of its narrow line luminosity and extended radio power BL Lacertae falls well within the region covered by the SDSS/NVSS sample (see Fig. 5), although at a slightly higher $L$[O III] than the region of higher galaxies density.

However, these SDSS/NVSS sources do not show prominent broad lines like those observed in BL Lacertae. Because from the point of view of its radio flux "misaligned BL Lacertae" objects would be included in the SDSS/NVSS catalogue even if located up to a redshift of ~0.2, the only possibility before we conclude that BL Lacertae is a unique object, at least in the nearby Universe, is that "misaligned BL Lacertae" objects were rejected on an optical basis.

Indeed, Best et al. (2005) excluded from their sample sources recognised by the automated SDSS classification pipeline as QSO, because a bright nucleus prevents a detailed study of the host properties. These objects instead generally do show broad lines. Hence one may wonder whether it is possible that the parent population of BL Lacertae can be found among them. We have then selected from the DR7 of the SDSS[8] all objects classified as QSO with redshift $z < 0.1$, resulting in 1033 sources, 90 of which have a radio source in the NVSS catalogue brighter than 5 mJy within 15″. We then looked for objects with properties similar to BL Lacertae, filtering out 42 sources with $r$ band and/or radio luminosities more than four times fainter than BL Lacertae, and 13 well-defined spiral galaxies, ending up with 35 candidates.

We downloaded their spectra from the SDSS public archive. Despite their automated classification as QSO, only 18 of them do show prominent broad emission lines[9]. These galaxies, however, have [O III] luminosity far higher than BL Lacertae, within the range $L$[O III] $\sim 2\times10^{41}$–$4\times10^{42}$ erg s$^{-1}$ (with a median of $\sim5\times10^{41}$ erg s$^{-1}$), a factor of 5 to 100 higher than in BL Lacertae, and are also characterized by a HEG spectrum. These sources have line and radio luminosities as well as line ratios typical of Seyfert galaxies (e.g. Whittle 1985)[10].

Summarizing, we did not find any object in the SDSS/NVSS sample with isotropic properties similar to BL Lacertae. In particular, only a few sources show broad emission lines and at the same time a luminosity of the host galaxy and a radio power at least a quarter of BL Lacertae; however, their narrow line luminosities exceed that of BL Lacertae on average by a factor of 12, and their HEG spectrum contrasts with the tentative identification of BL Lacertae as LEG. Because, as mentioned above, "misaligned BL Lacertae" objects would be found in this extensive catalogue, we must conclude that we failed to find the parent population of BL Lacertae, which apparently stands out as an "orphan" AGN.

This result contrasts with the requirement that to each object observed with its jet (characterized by a bulk Lorentz factor Γ) forming a small angle with our line of sight a parent population of mis-aligned objects must correspond. Although in presence of nuclear obscuration not all of them would show broad lines, this population is expected to be formed by $N \sim \Gamma^2 \sim$ 16–1000 sources, having assumed a range of $\Gamma \sim 4$–30 from Jorstad et al. (2005).

## 4. Summary and conclusions

More than a decade ago Vermeulen et al. (1995) and subsequently Corbett et al. (1996, 2000) detected a broad Hα emission line in the spectra of BL Lacertae. This luminous line should have been detected in previous spectra, suggesting that its flux must have increased by at least a factor 5 since 1989. The luminous Hα line suggested a Seyfert-like nucleus in BL Lacertae, complicating the already difficult task of understanding what AGN population this object (and BL Lac objects in general) belongs to, considering that FR I generally do not show broad lines.

[7] Sloan Digital Sky Survey, Data Release 2 (York et al. 2000), National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (Condon et al. 1998), and the Faint Images of the Radio Sky at Twenty centimeters survey (Becker et al. 1995), respectively.

[8] Note that the DR7 includes about four times more galaxies than the DR2 considered above.

[9] For the remaining 17 galaxies, we set upper limits to their broad Hα luminosities fitting multiple emission lines to the spectra obtained after subtraction of the stellar component, as in Buttiglione et al. (2010). All limits are between $\sim10^{40}$ and $10^{41}$ erg s$^{-1}$.

[10] We remark one apparent exception, namely SDSS J122358.97+404409.3, with $L$[O III] only 20% smaller than BL Lacertae, However, this object has a strong contamination by its active nucleus; the equivalent width ($EW$) of the NaD feature is $EW$(NaD) = 1.04 Å, strongly reduced by the dilution of its nuclear emission with respect to a typical value for early type galaxies of ~4 Å, indicating a nuclear contribution of ~80%. Its $r$ band magnitude corrected for the nuclear contribution is $M_{\rm R} = -20.7$, nearly 2 mag below the host of BL Lacertae.

To investigate this matter we acquired low- and high-resolution spectra of BL Lacertae with the TNG during four nights in 2007–2008, when the source optical brightness was $R \sim 14-14.5$. Our spectra confirm the presence of a luminous H$\alpha$ broad line of $\sim 4 \times 10^{41}$ erg s$^{-1}$ and $FWHM \sim 4600$ km s$^{-1}$, as well as several narrow emission lines. Through a critical comparison of our data with those by Corbett et al. (2000), we concluded that the BLR luminosity has increased by ~50% in about ten years. This level of variability is not unusual for Broad Lined AGN and it does not necessarily implies an evolutionary trend.

Then we examined the nuclear properties of BL Lacertae. The relationship between the SMBH mass and bulge luminosity in AGNs allowed us to derive a mass of $4-6 \times 10^8$ $M_\odot$. Using the spectroscopic information to calculate the virial mass, we instead obtained a value about 20–30 times lower. To understand the reason of this discrepancy we analysed the disc and BLR properties of other AGNs, and concluded that the BLR of BL Lacertae is underluminous by a factor 70–300.

Finally, we analysed the physical quantities that do not depend on orientation and beaming, and thus should also characterize the parent population of BL Lacertae. We defined diagnostic indices with the most reliable narrow emission lines, and found that their values provide a tentative identification of BL Lacertae as a LEG. Broad lines are instead observed only in HEG, but the diffuse radio luminosity of BL Lacertae is at least 100 times lower than in these powerful radio sources. On the other hand miniature radio galaxies are LEG, share both the narrow line and radio power properties of BL Lacertae, but they do not show a BLR. Taking into account how the miniature radio galaxy sample was selected, we expect that it should include "misaligned BL Lacertae" objects, unless they were excluded on the base of a QSO appearance. An analysis of the galaxy morphology, spectral features, and radio power of the QSO sources, initially discarded from the sample of miniature radio-galaxies, revealed that no object meets the requirements to represent the BL Lacertae parent population. Yet, for typical values of the Lorentz factor, we would expect 10–$10^3$ "misaligned BL Lacertae".

This leaves us with the only possibility that the observed properties of BL Lacertae are the result of a transient short lasting phase. We can envisage the following scenario, somewhat similar to that already suggested by Corbett et al. (1996). BL Lacertae in its initial state has properties similar to the sources of the SDSS/NVSS sample. Indeed, these are massive early-type galaxies and a large number of them have narrow lines and radio luminosities similar to that of BL Lacertae. From the point of view of their optical spectra they are LEG and lack broad lines. Subsequently (possibly ~20 years ago), its BLR underwent an increase of luminosity due to an increased amount of cold gas in the nuclear regions and/or to a higher level of ionizing continuum. These two effects may even be related and caused by a fresh input of accreting gas. The BLR structure might not have yet reached a stable configuration, accounting for its different properties when compared to other AGN. Also the NLR luminosity will grow with time and will also eventually change its state of ionization, but on a much larger timescale with respect to the BLR.

Based on the analysis of a single object it is clearly impossible to set a timescale for the duration of the putative bright phase. Furthermore, BL Lacertae was probably discovered since this object has been subject to repeated spectroscopic observations. However, our failure to find objects in the local Universe that might constitute its parent population suggests that the timescale associated with the period of high accretion must be orders of magnitude shorter than the lifetime of radio-loud AGN.

An alternative possibility is that the birth of the BLR marks the transition from a low-power radio galaxy to a high-power source. This would require a rapid increase in the luminosity of the large-scale radio structures to reach the level observed in e.g. the HEG of the 3CR sample, within a sufficiently short time so as not to produce a substantial population of transient sources. Instead, the available data rule out that BL Lacertae became an AGN only very recently, i.e. that we are witnessing its birth, because its radio emission extends ~10 kpc away from the core. This implies that this source is active since at least $\sim 3 \times 10^5$ years, assuming an expansion speed of 0.1 c.

We conclude that the parent population of BL Lacertae can be found among the large population of miniature radio-loud AGN forming the SDSS/NVSS sample, but this also requires that this object is experiencing a short transient phase. A continuation of the spectroscopic monitoring of this peculiar source caught in a crucial phase of its evolution can help us tremendously in our study of the physics and evolution of these systems.

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