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The Hybrid Nature of 0846+51W1: a BL Lac Object with a Narrow Line Seyfert 1 Nucleus *

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Abstract We found a NLS1 nucleus in the extensively studied eruptive BL Lac object, 0846+51W1, out of a large sample of NLS1s compiled from the spectroscopic dataset of SDSS DR1. Its optical spectrum can be well decomposed into three components: a power law component from the relativistic jet, a stellar component from the host galaxy, and a component from a typical NLS1 nucleus. The emission line properties of 0846+51W1, FWHM (Hβ) $\simeq$ 1710 km s^{-1} and $\frac{[\mathrm{OIII}]\lambda5007}{\mathrm{H}\beta} \simeq 0.32$ from its SDSS spectrum observed when it was in the faint state, fulfil the conventional definition of NLS1. Strong FeII emission is detected in the SDSS spectrum, which is also typical of NLS1s. We tried to estimate its central black hole mass using various techniques and found that 0846+51W1 is very likely emitting at a few $\times 10\%$ of the Eddington luminosity. We speculate that Seyfert-like nuclei, including NLS1s, might be concealed in a significant fraction of BL Lacs but have remained largely unobserved because, often, their optical-UV continuum is overwhelmed by the synchrotron emission.

Key words: galaxies: active – galaxies: Seyfert – galaxies: BL Lacertae – quasars: individual (0846+51W1) – radiation: lines, continuum

1 INTRODUCTION

In 1985, Osterbrock & Pogge identified a special class of active galactic nuclei (AGN) known as Narrow Line Seyfert 1 galaxies (NLS1s), which are characterized by their narrow Balmer emission lines (FWHM (Hβ) $\lesssim 2000\,\mathrm{km\,s^{-1}}$) and forbidden to permitted line ratios $\frac{[\mathrm{OIII}]\lambda5007}{\mathrm{H}\beta} \lesssim 3$ (for the conventional definition of NLS1s, see Pogge 2000). Subsequent studies revealed their extreme properties, such as the narrowest $H\beta$ line width, the weakest [OIII]λ5007, the strongest FeII emission and the steepest soft X-ray slope. These characteristics place the NLS1s at the

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extreme end of the Eigenvector 1 (E1) parameter space (Boroson & Green 1992; Sulentic et al. 2000) and their unusualness is very useful for testing the viability of AGN models.

It is found that radio-loud AGNs occupy a restrict E1 parameter space opposite to the NLS1s which are usually radio-quiet (Sulentic et al. 2003). Only three radio-loud NLS1s with radio-loudness (defined as $\frac{f_{\rm radio}}{f_{\rm optical}}$) between $\sim 10-100$ are known before 2000. They are all radio-intermediate sources according to the criterion of Sulentic et al. (2003). About 20 more radio-loud NLS1s were identified by Whalen et al. (2001) in the FIRST Bright Quasar Survey. Zhou & Wang (2002) found eight more radio-loud NLS1s by cross-correlating the Veron & Veron-Cetty AGN with the FIRST and NVSS radio catalog. Again, almost all of these newly extracted radio-loud NLS1s are moderate radio sources. It is remarkable that all of the discovered radio-loud NLS1s are compact at the present spatial resolution, indicating that relativistic beaming might be important in at least some of these objects. SDSS J0948+0022 is hitherto the only genuinely very radio-loud NLS1 that has possibly a relativistic jet beaming toward the observer (Zhou et al. 2003). These properties call to mind blazars, which are another small distinct subset of AGN.

Blazar is a picturesque term first proposed by Spiegel in 1978 to refer to rapidly variable objects (see Burbidge & Hewitt 1992), and all of the known blazars are radio sources. Nowadays it is believed that blazars, including OVVs (optically violent variables) and BL Lacs, are those AGNs that have a strong relativistically beamed component close to the line of sight. BL Lacs and OVVs share many common properties except that, by definition, emission lines are very weak or absent in the former. However, the rarity of very radio-loud NLS1s, whose occurrence in low redshift broad line AGN is estimated $\lesssim 0.2\%$ (Zhou et al. 2003), is an obstacle when we try to address this issue.

The large sky area coverage and moderate depth of the Sloan Digital Sky Survey (SDSS, York et al. 2000) make it useful for exploring rare objects, such as very radio-loud NLS1s. In this letter we report the discovery of another such object, 0846+51W1=SDSS J084957.98+510829.1, out of $\sim$ 500 NLS1s compiled from the spectroscopic dataset of the SDSS Data Release 1 (DR1). It is even more conspicuous than SDSS J0948+0022 (Zhou et al. 2003) and shows many dramatic properties.

Actually 0846+51W1 was originally found by Arp et al. (1979) and has been the subject of much study ever since. This object is violently variable in its optical flux ($\Delta V \sim 5^{\rm m}$ over a time span of $\sim$ 1 year, and $\Delta V \sim 4^{\rm m}$, from $V \simeq 15.8^{\rm m}$ to $V \sim 19.5^{\rm m}$ within one month). At its maximum light burst, the optical spectrum was found to be featureless, but emission lines were detected when it became fainter. Its optical slope varies dramatically from $\alpha_o \approx 1.6$ when the object is bright to $\alpha_o \approx 2.8$ when it is faint ($f_\nu \propto \nu^{-\alpha_o}$, c.f. Arp et al. 1979; Stickel et al. 1989). It is also found to be highly polarized in both the radio and optical bands (Moore & Stockman 1981; Sitko et al. 1984). Thus, 0846+51W1 bears all the characteristics of BL Lac object. However, the narrow wavelength coverage of Arp et al. and Stickel et al. led these authors to classify 0846+51W1 as a high redshift ($z = 1.86$) BL Lac object, but the SDSS spectrum clearly shows that its true redshift is $z = 0.5835$.

We will analysis the SDSS optical spectrum of 0846+51W1 in detail in Sect. 2. Some implications of the analysis are discussed in Sect. 3. The main purpose of this letter is to rekindle interest on this fascinating object. We adopt a Λ-dominated cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ through out this letter.

The SDSS Web site is http://www.sdss.org/.

2 OPTICAL SPECTRUM ANALYSIS

0846+51W1 is observed by SDSS only because it is the counterpart of a FIRST radio source. Its SDSS spectrum is shown in Fig. 1 (the thin line) with the recognizable emission lines labelled. At first sight, the optical spectrum of 0846+51W1 looked like a typical NLS1 and, though noisy, did not suggest any association with a BL Lac object. Almost all of the familiar emission lines, even the weak ones such as [NeV]λ3346, [NeV]λ3426, [NeIII]λ3869 and [NeIII]λ3888 are present in the spectrum. Optical and UV FeII multiplets can also be easily picked out. The spectrum was taken on 2002 November 29 and the visual magnitude estimated from the spectrum is about $19.8^{\rm m}$, indicating that 0846+51W1 was in its quiescent state then. At a redshift of $z = 0.5835$, its luminosity is $M_V \simeq -22.1^{\rm m}$, which is comparable to luminous CD galaxies indicating that the host may contribute significantly to the observed spectrum. Many authors invoke gravitational (micro) lenses to interpret the eruptive behavior of 0846+51W1 (e.g., Nottale 1986; Stickel et al. 1989). However, the HST image when 0846+51W1 was in its faint state ($V \simeq 19.7^{\rm m}$) and did not show significant resolved structure (Maoz et al. 1993). Moreover, with a broader wavelength coverage and a higher resolution, the SDSS spectrum does not show the signature of any intervening galaxy. Because the S/N ratio of the SDSS spectrum is not high (the median value of S/N ratio is only ~ 5 per pixel), we model it with three components

$$f(\lambda) = aA(\lambda) + bB(\lambda) + cC(\lambda), \tag{1}$$

where $A(\lambda)$ denotes a composite spectrum of NLS1s (c.f. Constantin & Shields 2003), $B(\lambda) \propto \lambda^{-0.5}$ is a power law component from the relativistic jets, $C(\lambda)$ is the elliptical galaxy template (c.f. Mannucci et al. 2001), and the three non-negative coefficients, a, b, and c, represent the relative contributions of the three components and are taken as adjustable. Emission lines except FeII multiplets are masked in the fitting procedure. The final fit is done through minimization of χ^2 taking account of the flux uncertainty. The result is acceptable and is also shown in Fig. 1.

Now the continuum subtracted spectrum is fitted to evaluate the parameters of the prominent emission lines. The Hβ +[OIII]$\lambda\lambda$ 4959, 5007 regime is fitted with one Lorentzian + three Gaussians. The Hβ is modelled by one Lorentzian (broad component) and one Gaussian (narrow component). The [OIII]$\lambda\lambda$4959, 5007 doublet are fitted with two Gaussians. The widths and redshifts of the three Gaussians are forced to be the same and the intensity ratio of the [OIII]$\lambda\lambda$4959, 5007 doublet is fixed to the theoretical value. We also force the ratio [OIII]λ5007 to Hβ narrow component to be equal to 10, which is the typical value of the Seyferts. This is a common procedure to prevent the fitting routine from yielding non-physical values when the spectrum is noisy (e.g., Veron et al. 2001). Like almost all known NLS1s, 0846+51W1 shows strong FeII emission. However, measurement of its FeII multiplets is still a challenge for the present spectrum quality. Judging from the fitting residuals of Equation (1), what we can say is that its optical FeII strength should be at least comparable to, and is possibly stronger than that of typical NLS1s. We did not analyse other emission lines because the quality of the spectrum is not high enough for us to draw any significant conclusion. The main parameters of the prominent emission lines are listed in Table 1.

Table 1 Emission Line Parameters of 0846+51W1

Line	Flux 10^{-17} erg s^{-1} cm^{-2}	FWHM km s^{-1}
[OIII]λ5007	45±4.7	372±31
Hβ (broad component)	139±22	1710±184
MgIIλ2800	286±39	2512±471
FeII$\lambda\lambda$4570	$\gtrsim$ 100	

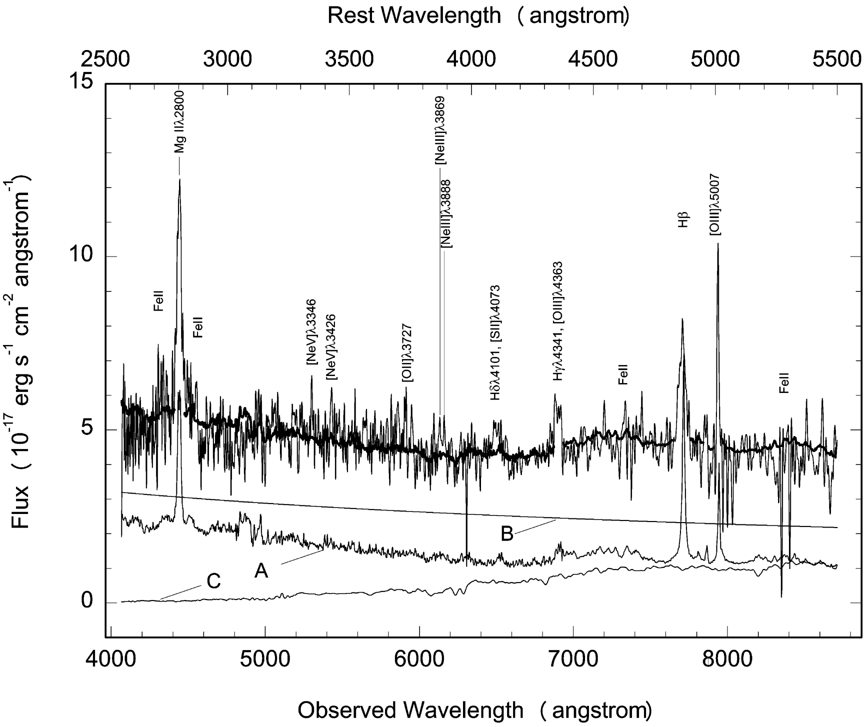

Fig. 1 Optical continuum of 0846+51W1 (the uppermost thin line) can be well decomposed into three components of A: average NLS1 spectrum, B: power law spectrum with spectral index $\alpha = 1.5$ ($f_\nu \propto \nu^{-\alpha}$) and C: elliptical template. The uppermost thick line is the sum of the three components.

3 DISCUSSION

3.1 THE CENTRAL BLACK HOLE MASS AND THE ACCRETION RATE OF 0846+51W1

Mass estimates for the central black holes in AGN have become feasible using various techniques and the exact value of $M_{\rm BH}$ of 0846+51W1 is of much interest, considering its dual role of NLS1 and BL Lac object. We will try to estimate $M_{\rm BH}$ using three distinct approaches and compare the results yielded.

We first use the virial assumption with the measure FWHM (Hβ) and the decomposed luminosity of the disk component ("A" component in Sect. 2). Then $M_{\rm BH}$ can be estimated as (Kaspi et al. 2000)

$$M_{\rm BH} = 1.464 \times 10^5 \Big(\frac{R_{\rm BLR}}{\rm lt-days}\Big)\Big(\frac{v_{\rm FWHM(H\beta)}}{10^3\ {\rm km\ s^{-1}}}\Big)^2\ M_\odot, \tag{2}$$

where $R_{\rm BLR}$ is the size of the broad Hβ emission line region which is related to the monochromatic luminosity of "A" component through the empirical relation (Kaspi et al. 2000 converted to our adopted cosmology)

$$R_{\rm BLR} = 22.3\Big[\frac{\lambda L_\lambda(5100{\rm \AA})}{10^{44}{\rm erg\ s^{-1}}}\Big]^{0.7}\ {\rm lt-days}. \tag{3}$$

For the measured value of $S_\lambda(5100{\rm \AA}) \simeq 1.2\times10^{-17}$ erg s cm^{-2} Å ("A" component) and FWHM (Hβ) $\simeq$ 1710 km s^{-1} we obtain $M_{\rm BH} \simeq 8.2 \times 10^6\ M_\odot$.

The second method to estimate $M_{\rm BH}$ is to use [OIII]λ5007 as a surrogate for the stellar velocity dispersion of the bulge σ_* and the $M_{\rm BH} - \sigma_*$ correlation (Tremaine et al. 2002)

$$\log\Big(\frac{M_{\rm BH}}{M_\odot}\Big) = (8.13 \pm 0.06) + (4.02 \pm 0.32)\log\Big(\frac{\sigma_*}{200\ {\rm km\ s^{-1}}}\Big). \tag{4}$$

If the motion of [OIII] emission line clouds in the NLR of the AGN is dominated by the gravitational potential of the host galaxy bulge, a strong correlation between the FWHM [OIII] and σ_* would be expected and such a correlation is indeed found by Nelson & Whittle (1996). Nelson (2000) suggested that the FWHM [OIII] may be used as a surrogate for σ_* by the relation

$$\sigma_* \sim \frac{\rm FWHM[OIII]}{2.35}. \tag{5}$$

Using Eqs. (3) and (4) we obtain $M_{\rm BH} \simeq 5.2 \times 10^7\ M_\odot$.

The third way to estimate $M_{\rm BH}$ is to use the $M_{\rm BH}$–$M_{\rm bulge}$ correlation. $M_{\rm bulge}$ can be deduced from the adopted L/M ratio of elliptical galaxies where L refers to the "C" component (Sect. 2). Using the following empirical relation (Laor 2001 converted to our adopted cosmology)

$$M_V({\rm bulge}) = -10.06 \pm 1.08 - (1.38 \pm 0.13){\rm log}\Big(\frac{\rm M_{BH}}{\rm M_\odot}\Big) \tag{6}$$

with the decomposed host luminosity of M_V(bulge) $\simeq -20.5^{\rm m}$, we obtain $M_{\rm BH} \simeq 4.3\times10^7\ M_\odot$.

Considering the large uncertainty of these techniques ($\sim 0.4 - 0.7$ dex, Vestergaard 2004), the estimated values of $M_{\rm BH}$ are consistent with each other. Because its nonthermal emission is highly boosted, it is difficult to estimate the bolometric luminosity of 0846+51W1 and we use the emission of "A" component to yield a lower limit. Assuming that the bolometric luminosity is about nine times of the monochrome luminosity at the B-band (Elvis et al. 1994), the Eddington mass $M_{\rm Edd}$ should be $> 5.3 \times 10^6 M_\odot$. Hence 0846+51W1 should be emitting at $>$ 10% of the Eddington luminosity.

3.2 On the Hybrid Nature of 0846+51W1

The SDSS spectrum of 0846+51W1 is typical of NLS1s. The width of Hβ, FWHM (Hβ) $\approx$ 1700 km s^{-1} is narrower than in the normal broad line AGN and the flux ratio of [OIII]/H$\beta \approx 0.3$ excludes the possibility that it might be a type 2 AGN. The primary ionization source should be the thermal component from the accretion disk because the small blue bump is clearly present. However, its soft X-ray photon index $\Gamma_{0.2-2.4\mathrm{keV}} = 0.61^{+0.38}_{-0.49}$ is very flat. Such a difference between 0846+51W1 and "normal" NLS1s can be anticipated because in the X-ray we may observe mainly the jet emission as in other BL Lacs.

Considering that NLS1s show extreme characteristics opposite to classical radio-loud AGN, the nature of radio sources in 0846+51W1 is of particular interest. Accumulated evidence indicates that the physical driver of Eigenvector 1 may be the accretion rate of the active nuclei, with the source orientation playing a concomitant role and NLS1s are believed to have large $\dot{m} \equiv \frac{\dot{M}}{M_{\mathrm{BH}}}$ and small inclination angle i. This may be exactly the case with 0846+51W1 and the other very radio-loud NLS1, SDSS J0948+0022. The radio power of 0846+51W1 of $P_{5\mathrm{GHz}} \sim 3.9 \times 10^{26}\mathrm{W\ Hz}^{-1}$ (the radio fluxes are adopted from Arp et al. 1979 and Gregory & Condon 1991) is comparable to SDSS J0948+0022, which is also a highly variable object (Zhou et al. 2003). It has been found that in quasars with no Doppler boosting, the luminosity of $H\beta$ is tightly correlated with the continuum luminosity with the median rest-frame $H\beta$ equivalent width $EW_{\mathrm{H}\beta} \sim 80$ Å (Veron-Cetty & Veron 2000). We note that $EW_{H\beta} \simeq 18$ Å of 0846+51W1 and 25 Å of SDSS J0948+0022 are both much less than the above median value. This indicates that the synchrotron emission from relativistic jet might make significant contribution to the optical continuum. Indeed, we would have $EW_{H\beta} \simeq 73$ Å for 0846+51W1 if the underling continuum of "A" component is used in the calculation. We argue that 0846+51W1 and SDSS J0948+0022 are actually NLS1s oriented with the jet axis almost along our line of sight and consequently are extremely beamed and hence the blazar-like behavior. If the Doppler factor is $\gtrsim 10$, the intrinsic radio luminosity of these two objects would be around the FR I/FR II transition.

Arp et al. (1979) found that 0846+51W1 fulfils four of the five criteria for BL Lac object, i.e., weak line feature, large amplitude variability, nonthermal continuum and red color (polarization measures were not available then), so there were strong arguments for classifying 0846+51W1 as a BL Lac object. A high polarization of $> 10\%$ was later detected in the optical and radio by Moore & Stockman (1981) and Sitko et al. (1984). According to the current unified scheme of AGN, the parent population of blazars are radio galaxies (RGs) and radio-loud quasars (RLQs). Fanaroff & Riley (1974) classified the radio morphology of RGs and RLQs into two categories: FR IIs are the classical double radio sources with edge-bright lobes while FR Is have edge-darkened morphologies. BL Lacs are taken as "beamed" FR I radio galaxies while OVVs as beamed FR IIs. The main difference between the two is believed to be the accretion rate, which is rather small in the former. For $\dot{m} \lesssim 1\%$, the accretion flow is advection dominated with small radiative efficiency. In this scenario, neither FR I nor BL Lac can be associated with an optically powerful quasar. However, broad line AGNs and high luminous quasars associated with FR I radio structure have been reported in recent year (Lara et al. 1999; Blundell & Rawlings 2001). Correspondingly, broad emission lines have also been detected in dozens of BL Lacs and even in BL Lacertae itself (see tables 3 and 4 of Veron-Cetty & Veron 2000).

BL Lacs are conventionally defined as blazars with rest-frame emission line equivalent widths smaller than 5 Å (Morris et al. 1991). The distribution of emission line equivalent width in the blazars is obviously not bimodal and the strength of the highly variable synchrotron continuum can further blur such an arbitrary boundary. Objects that fulfil the above criterion may form a rather complex family. While the emission line properties of some BL Lacs mimic LINERs indicating low mass accretion rate, other BL Lacs including the prototype one may harbor a Seyfert-like nucleus (e.g., Corbett et al. 2000). Some of the BL Lacs with Seyfert-like nucleus may have a relatively high accretion rate but, in the optical-UV band, the emission lines and thermal continuum from the hot accretion disc can be overwhelmed by the Doppler-boosted synchrotron component some of the time. Here 0846+51W1 represents the rare case where the synchrotron continuum happened to be faint enough for the NLS1 nucleus to reveal itself. Similar to 0846+51W1 which is likely emitting at near Eddington luminosity, Blundell & Rawlings (2001) found a powerful optical quasar E1821+643 associated with a FR I radio structure, indicating that relatively high accretion rate can also occur in FR Is.

It is remarkable that, on the one hand, no highly radio-luminous FR Is have been found as yet, and on the other hand, no NLS1s have been reported to be very powerful in the radio except SDSS J0948+0022 and 0846+51W1 which are strongly boosted and their intrinsic radio luminosity may not be too high. This suggests that apart from other properties such as the spin rate of the central black hole, the mass accretion rate also plays a role in determining the radio power and morphology. When $\dot{m} \ll \dot{m}_{\rm Edd}$, only low power jets can be produced because there is not enough input energy, and these can be easily disrupted and dissipated within a short distance from the core, forming an FR I source (De Young 1993). On the other hand, under the condition of near or supper Eddington accretion, the gas rich environment of the inner region may affect the collimation and propagation of the jet, turning it into an outflow in some extreme cases. In 0846+51W1 and SDSS J0948+0022 we are very likely observing the innermost part of a jet pointing toward us, and the fact that all radio sources in NLS1s are compact can be understood on this interpretation. We speculate that, while both low and high mass accretion can occur in FR Is and in their beamed cousins BL Lacs, the accretion rate of FR IIs can only (at one time) be moderately high. It has been pointed by Blundell & Rawlings (2001) that optically luminous FR I quasars are very much under-investigated. We speculate that Seyfert-like nuclei might be concealed in a significant fraction of BL Lacs but this possibility has not been sufficiently explored due to the fact that, by definition, the optical-UV continuum of this kind of objects is often overwhelmed by the synchrotron emission. A few of these objects may be "very" radio-loud NLS1s provided they are observed at very small inclination angles.

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