Hybrid nature of 0846+51W1: a BL Lac object with a narrow line Seyfert 1 nucleus

Hong-Yan Zhou, Ting-Gui Wang, Xiao-Bo Dong, Cheng Li, and Xue-Guang Zhang

mtzhou@ustc.edu.cn

Center for Astrophysics, University of Science and Technology of China, Hefei, 230026, China

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ABSTRACT

We found a NLS1 nucleus in the extensively studied eruptive BL Lac, 0846+51W1, out of a large sample of NLS1 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, $FWHM(H\beta) \simeq 1710 \text{ km s}^{-1}$ and $\frac{[O\text{III}]\lambda5007}{H\beta} \simeq 0.32$ according to its SDSS spectrum observed when it was in faint state, fulfill the conventional definition of NLS1. Strong FeII emission is detected in the SDSS spectrum, which is also typical of NLS1s. We try to estimate its central black hole mass using various techniques and find that 0846+51W1 is very likely emitting at a few $\times 10\%$ of Eddington luminosity. We speculate that Seyfert-like nuclei, including NLS1s, might be concealed in a significant fraction of BL Lacs but have not been sufficiently explored due to the fact that, by definition, the optical-UV continuum of such kind of objects are often overwhelmed by the synchrotron emission.

Subject headings: 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) denominated as Narrow Line Seyfert 1 galaxies (NLS1s), which are characterized by their narrow Balmer emission line width of $FWHM(H\beta) \lesssim 2000 \text{ km s}^{-1}$ and forbidden to permitted line ratio $\frac{[OIII]_\lambda5007}{H\beta} \lesssim \frac{1}{3}$ (for the conventional definition of NLS1s, see Pogge 2000). Succedent studies reveal their extreme properties, such as the narrowest $H\beta$ line width, the weakest $[OIII]_\lambda5007$, the strongest FeII emission and the steepest soft X-ray slope. These characteristics locate NLS1s at the extreme end of the Eigenvector 1 (E1) parameter space (Boroson & Green 1992; Sulentic et al. 2000) and their unusualness is very useful to test the viabilities of AGN models.

It is found that radio-loud AGN occupy a restrict E1 parameter space opposite to NLS1s which are usually radio-quiet (Sulentic et al. 2003). Only three radio-loud NLS1s with radio-loudness (defined as $\frac{f_{\text{radio}}}{f_{\text{optical}}}$) between $\sim 10 - 100$ are known before 2000. They are all radio-intermediate sources according to the criterion of Sulentic et al (2003). About twenty 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 dig out 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 possibly with a relativistic jet beaming toward the observer (Zhou et al. 2003). These properties call to remembrance of blazar, which is another small divertive subset of AGN.

Blazar is a pictorial term first proposed by Spiegel in 1978 be applied 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 AGN 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, in the former emission line is very weak or absent. 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 in the way addressing ourselves to this problem.

The large sky area coverage and moderate deepness of the Sloan Digital Sky Survey (SDSS$^1$, York et al. 2000) make it be propitious to 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 J094857.3+002225 and shows many dramatic properties.

Actually 0846+51W1 was originally found by Arp et al. (1979) and has been the subject of much study since then. This object is violently variable in its optical flux ($\Delta V \sim 5^m$ over a time span of $\sim 1$ year and $\Delta V \sim 4^m$, from $V \simeq 15^m.8$ to $V \sim 19^m.5$ within one month). At its maximum light burst, the optical spectrum was found to be featureless, while emission lines were detected when it became fainter. Its optical slope may vary 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 of the radio and optical bandpass (Moore & Stockman 1981; Sitko et al. 1984). Therefore 0846+51W1 bears all the characteristics of BL Lac object. However, the narrow wavelength coverage of Arp et al. and Stickel et al. led 0846+51W1 be taken as a high redshift BL Lacs ($z=1.86$) by these authors whereas the SDSS spectrum clearly shows that its true redshift is $z = 0.5835$.

$^1$The SDSS Web site is http://www.sdss.org/.
We will analysis the SDSS optical spectrum of 0846+51W1 in detail in §2. Some implication of 0846+51W1 is discussed in §3. The main purpose of this letter is to reignite further interest to this fascinating object. We adopt a Λ-dominated cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ throughout this letter.

2. OPTICAL SPECTRUM ANALYSIS

0846+51W1 is observed by SDSS only because it is the counterpart of a FIRST radio source and its SDSS spectrum is shown in Figure 1 (denoted as thin line) with recognizable emission lines labelled. At first sight, the optical spectrum of 0846+51W1 looks like a typical NLS1 and by no means let any association with a BL Lacertae occur to us though the spectrum is rather noisy. Almost all of the familiar emission lines, even the weak ones such as [NeV]$\lambda$3346, [NeV]$\lambda$3426, [NeIII]$\lambda$3869 and [NeIII]$\lambda$3888 are present in the spectrum. Optical and UV FeII multiplets can also be easily spotted out. The spectrum were taken at 2002 November 29 and the visual magnitude estimated from the spectrum is about $19^m.8$ indicating that 0846+51W1 was in its quiescent state when it was observed. At a redshift of $z = 0.5835$, its luminosity is $M_V \simeq -22^m.1$, 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 ($V \simeq 19^m.7$) did not show significant resolved structure (Bahcall et al. 1993) and, with broader wave coverage and 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, we model it with three components

$$f(\lambda) = aA(\lambda) + bB(\lambda) + cC(\lambda)$$  \hspace{1cm} (1)
where $A(\lambda)$ denotes a composite spectrum of NLS1 (cf. Constantin & Shields 2003), $B(\lambda) \propto \lambda^{-0.5}$ is a power law component from the relativistic jets, $C(\lambda)$ is the template of elliptical galaxy (cf. Mannucci et al. 2001) and $a$, $b$, and $c$ represent the relative contribution of the three components which are set free. Emission lines except FeII multiplets are masked in the fitting procedure. The final fit is done through minimization of $\chi^2$ and the result is acceptable (reduced $\chi^2 = 1.36$) and is also shown in Figure 1.

Now the continuum subtracted spectrum is fitted to measure prominent emission line parameters. The $H\beta + [OIII] \lambda\lambda 4959, 5007$ regime is fitted with one Lorentzian + three Gaussians. The $H\beta$ is modelled by one Lorentzian (broad component) and one Gaussian (narrow component) and the $[OIII] \lambda\lambda 4959, 5007$ doublet are fitted with two Gaussians. The width and redshift 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 of $[OIII] \lambda 5007$ to $H\beta$ narrow component to be equal to 10, which is the typical value of Seyferts. This is a common procedure to prevent the fitting routine to yield non-physical value when spectrum is noisy (e.g., Veron et al. 2001). Almost all known NLS1s show strong FeII emission as does 0846+51W1. However, measurement of its FeII multiplets is rather challenged for the present spectral quality. Judging from the fitting residual of Equation (1), what we can say is that its optical FeII strength should be at least comparable to, possibly stronger than that of typical NLS1s. We did not analyses other emission lines because the quality of the spectrum is not high enough for us to draw any significant conclusion. The main parameters of prominent emission lines are listed in Table 1.
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 $M_{BH}$ of 0846+51W1 is of much interesting considering its dualism of NLS1 and BL Lac object. We will try to estimate $M_{BH}$ using three distinct approaches and make comparison among the results yielded.

We first use the virial assumption with FWHM($H\beta$) measured and the decomposed luminosity of the disk component ("A" component of §2). Then $M_{BH}$ can be estimated as (Kaspi et al. 2000)

$$M_{BH} = 1.464 \times 10^5 \left( \frac{R_{BLR}}{lt - days} \right) \left( \frac{v_{FWHM(H\beta)}}{10^3 kms^{-1}} \right)^2 M_\odot$$

(2)

where $R_{BLR}$ is the size of broad $H\beta$ 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)

$$R_{BLR} = 22.3 \left( \frac{\lambda L_{\lambda(5100\AA)}}{10^{44} ergs^{-1}} \right)^{0.7} lt - days$$

(3)

Table 1. Emission line parameters of 0846+51W1.

| line         | Flux       | FWHM  |
|--------------|------------|-------|
| $[OIII]\lambda5007$ | 45±4.7     | 372±31 |
| $H\beta$(broad component) | 139±22     | 1710±184 |
| $MgII\lambda2800$        | 286±39     | 2512±471 |
| FeII$\lambda4570$        | $\gtrsim$ 100 |       |
For the measured value of $S_\lambda(5100\AA) \simeq 1.2 \times 10^{-17} \ erg\ s\ cm^{-2}\ \AA$ ("A" component) and $FWHM(H\beta) \simeq 1710\ km\ s^{-1}$ we obtain $M_{BH} \simeq 8.2 \times 10^6\ M_\odot$.

The second method to estimate $M_{BH}$ is to use $[OIII]\lambda5007$ as a surrogate for the stellar velocity dispersion of the bulge $\sigma_*$ and the $M_{BH}-\sigma_*$ correlation (Tremaine et al. 2002)

$$\log\left(\frac{M_{BH}}{M_\odot}\right) = (8.13 \pm 0.06) + (4.02 \pm 0.32)\log\left(\frac{\sigma_*}{200\ km\ s^{-1}}\right)$$

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

$$\sigma_* \sim \frac{FWHM[OIII]}{2.35}$$

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

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

$$M_V(bulge) = -10.06 \pm 1.08 - (1.38 \pm 0.13)\log\left(\frac{M_{BH}}{M_\odot}\right)$$

with the decomposed host luminosity of $M_V(bulge) \simeq -20^{m}.5$, we got $M_{BH} \simeq 4.3 \times 10^7\ M_\odot$.

Considering the large uncertainty of these techniques ($\sim 0.4 - 0.7$ dex, Vestergaard 2004), the estimated values of $M_{BH}$ 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 its lower limit. Assuming that the bolometric luminosity is about nine times of the monochrome luminosity at B-band (Elvis
et al. 1994), the Eddington mass $M_{Edd}$ should be $> 5.3 \times 10^6 M_\odot$. Hence 0846+51W1 should emit at $> 10\%$ of Eddington luminosity.

3.2. On the hybrid nature of 0846+51W1

The SDSS spectrum of 0846+51W1 is typical of NLS1s. The width of $H\beta$, $FWHM(H\beta) \approx 1700 \text{km}s^{-1}$ is narrower than 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 little blue bump clearly presents itself. However, its soft X-ray photon index $\Gamma_{0.2-2.4keV} = 0.61^{+0.38}_{-0.49}$ is very flat. Such a difference between 0846+51W1 and “normal” NLS1s can be anticipated because in the X-ray we may be observing 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 interesting. Accumulated evidence indicates that the physical driver of Eigenvector 1 may be the accretion rate of active nuclei, with source orientation playing a concomitant role and NLS1s are believed to have large $\dot{m} \equiv \frac{\dot{M}}{M_{BH}}$ and small inclination angle $i$. It may be exactly the case of 0846+51W1 and the other very radio-loud NLS1, SDSS J0948+0022. The radio power of 0846+51W1 $P_{5GHz} \sim 3.9 \times 10^{26} W H z^{-1}$ (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 $EW_{H\beta} \sim 80 \text{Å}$ (Veron-Cetty & Veron 2000). We note that $EW_{H\beta} \simeq 18 \text{Å}$ of 0846+51W1 and 25 Å of SDSS J0948+0022 are both much less than the above median value. This indicates that synchrotron emission from
relativistic jet might make significant contribution to the optical continuum. Indeed, we would have $EW_{H\beta} \approx 73$ Å for 0846+51W1 if the underlying continuum of ”A” component is used in calculation. We argue that 0846+51W1 and SDSS J0948+0022 are actually NLS1s oriented with jet axis almost along our line of sight and consequently extremely beamed and henceforth show 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, except that polarization measures were not available then and strongly argued that 0846+51W1 should be classified as a BL Lac object. High polarization of $> 10\%$ was also detected in the optical and radio by Moore & Stockman (1981) and Sitko et al. (1984). According to the current unified schemes of AGN, the parent population of blazar are radio galaxies (RGs) and radio-loud quasars (RLQs). The radio morphology of RGs and RLQs are classified to two categories according to Fanaroff & Riley (1974): 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 deference 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 optically powerful quasar. However, broad line AGN and high luminous quasar 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 Table 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 blazar 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 relatively high accretion rate but, in 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. 0846+51W1 is the rare case at it happens when the synchrotron continuum became faint enough for the NLS1 nucleus to reveal itself. In accordance with 0846+51W1 which is likely emitting at near Eddington luminosity, Blundell & Rawlings (2001) found that a optical powerful quasar E1821+643 is 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 NLS1 has 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, mass accretion rate play an role in determining the radio power and morphology. When $\dot{m} \ll \dot{m}_{\text{Edd}}$, only low power jet can engender because there is not enough input energy, which can be easily disrupted and dissipated within short distance from the core and forms an FR I source (De Young 1993). Contrarily, under the condition of near or supper Eddington accretion, neither does the air rich environment lend itself to the collimation and propagation of the jet, which may be translated into outflow in some extreme cases. In 0846+51W1 and SDSS J0948+0022 we are very likely observing the innermost part of the jet pointing toward us and the fact that all of the radio sources in NLS1s are compact can be understood according to this interpretation. We speculate
that, while both low and high mass accretion can occur in FR Is and 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 well under-investigated. We speculate that Seyfert-like nuclei might be concealed in a significant fraction of BL Lacs but have not been sufficiently explored due to the fact that, by definition, the optical-UV continuum of such kind of objects are often overwhelmed by the synchrotron emission. A few of these objects may be ”very” radio-loud NLS1s provided that they are observed at very small inclination angle.

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REFERENCES

Arp, H., Sargent, W. L. W., Willis, A. G., & Oosterbaan, C. E. 1979, ApJ, 230, 68

Blundell, K. M. & Rawlings, S. 2001, ApJ, 562, L5

Boroson, T. A. & Green, R. F. 1992, ApJS, 80, 109

Burbidge, G. & Hewitt, A. 1992, Variability of Blazars, 4

Constantin, A. & Shields, J. C. 2003, PASP, 115, 592

Corbett, E. A., Robinson, A., Axon, D. J., & Hough, J. H. 2000, MNRAS, 311, 485

Fanaroff, B. L. & Riley, J. M. 1974, MNRAS, 167, 31P

Gregory, P. C. & Condon, J. J. 1991, ApJS, 75, 1011

Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631

Laor, A. 2001, ApJ, 553, 677

Lara, L., Marz´quez, I., Cotton, W. D., Feretti, L., Giovannini, G., Marcaide, J. M., & Venturi, T. 1999, New Astronomy Review, 43, 643

Mannucci, F., Basile, F., Poggianti, B. M., Cimatti, A., Daddi, E., Pozzetti, L., & Vanzi, L. 2001, MNRAS, 326, 745

Moore, R. L. & Stockman, H. S. 1981, ApJ, 243, 60

Morris, S. L., Stocke, J. T., Gioia, I. M., Schild, R. E., Wolter, A., Maccacaro, T., & della Ceca, R. 1991, ApJ, 380, 49

Nelson, C. H. & Whittle, M. 1996, ApJ, 465, 96
Nelson, C. H. 2000, ApJ, 544, L91

Nottale, L. 1986, A& A, 157, 383

Osterbrock, D. E. & Pogge, R. W. 1985, ApJ, 297, 166

Pogge, R. W. 2000, New Astronomy Review, 44, 381

Sitko, M. L., Rudnick, L., Jones, T. W., & Schmidt, G. D. 1984, PASP, 96, 402

Stickel, M., Fried, J. W., & Kuehr, H. 1989, A&A, 224, L27

Sulentic, J. W., Zamfir, S., Marziani, P., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2003, ApJ, 597, L17

Sulentic, J. W., Zwitter, T., Marziani, P., & Dultzin-Hacyan, D. 2000, ApJ, 536, L5

Véron-Cetty, M. P. & Véron, P. 2000, A&A Rev., 10, 81

Vestergaard M. 2004, astro-ph/0401436

Whalen, J., Laurent-Muheleisen, S. A., Moran, E. C., & Becker, R. H. 2001, Bulletin of the American Astronomical Society, 33, 1373

York, D. G. et al. 2000, AJ, 120, 1579

Zhou, H. & Wang, T. 2002, Chinese Journal of Astronomy and Astrophysics, 2, 501

Zhou, H., Wang, T., Dong, X., Zhou, Y., & Li, C. 2003, ApJ, 584, 147

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Fig. 1.— Optical continuum of 0846+51W1 (the uppermost thin line) can be well decomposed into three components of A: average NLS1 spectrum, B: spectral index of $\alpha = 1.5$ power law spectrum ($f_\nu \propto \nu^{-\alpha}$) and C: elliptical template. The uppermost thick line is the sum of the three components.
Fig. 2.— Both of $H\beta$ and MgII can be well fitted with Lorentz profile and the line widths are typical of NLS1s.