# NARROW DOUBLE-PEAKED EMISSION LINES OF SDSS J131642.90+175332.5: SIGNATURE OF A SINGLE OR A BINARY AGN IN A MERGER, JET–CLOUD INTERACTION, OR UNUSUAL NARROW-LINE REGION GEOMETRY

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## ABSTRACT

We present an analysis of the active galaxy SDSS J131642.90+175332.5, which is remarkable because all of its narrow emission lines are double-peaked, and because it additionally shows an extra broad component (FHWM $\sim$ 1400 km s$^{-1}$) in most of its forbidden lines, peaking in between the two narrow systems. The peaks of the two narrow systems are separated by 400–500 km s$^{-1}$ in velocity space. The spectral characteristics of double-peaked [O III] emission have previously been interpreted as a signature of dual or binary active galactic nuclei (AGNs), among other models. In the context of the binary scenario, SDSS J131642.90+175332.5 is a particularly good candidate because not just one line but all of its emission lines are double-peaked. However, we also discuss a number of other scenarios which can potentially account for double-peaked narrow emission lines, including projection effects, a two-sided outflow, jet–cloud interactions, special narrow-line region (NLR) geometries (disks, bars, or inner spirals), and a galaxy merger with only *one* AGN illuminating *two* NLRs. We argue that the similarity of the emission-line ratios in both systems, and the presence of the very unusual broad component at intermediate velocity, makes a close pair of unrelated AGNs unlikely, and rather argues for processes in a single galaxy or merger. We describe future observations that can distinguish between these remaining possibilities.

*Key words:* galaxies: active – galaxies: evolution – galaxies: individual (SDSS J131642.90+175332.5) – quasars: emission lines

## 1. INTRODUCTION

According to hierarchical models of galaxy formation, galaxies will merge frequently with each other, forming supermassive binary black holes (SMBBHs) at their centers. The merging of the two SMBHs would proceed in three stages (Begelman et al. 1980). After an initial phase of merging of the galaxy cores by dynamical friction, the two SMBHs would form a bound pair. The duration of this second phase is still uncertain and depends on the efficiency of gas- or stellar-dynamical processes to aid shrinking the binary orbit and prevent the SMBHs from stalling (e.g., Merritt & Milosavljević 2005). Once they reach a separation of about 0.01 pc, emission of gravitational waves will lead to the coalescence of the two black holes within a relatively short time interval (e.g., Sathyaprakash & Schutz 2009). Measuring the frequency of wide and close pairs of SMBHs, and their properties, is therefore important in the context of understanding galaxy mergers and mechanisms of active galactic nucleus (AGN) fueling in dependence of the merger phase. It also allows us to constrain timescales of SMBH merging and coalescence, and to estimate the fraction of gravitational wave sources detectable with the *Laser Interferometer Space Antenna* mission.

The search for binary AGNs and SMBBHs has therefore received great attention, yet few definite cases are known. In recent years, a few pairs of accreting SMBHs have been found at the centers of single galaxies based on spatially resolved X-ray, radio, and optical imaging spectroscopy, namely, NGC 6240 (Komossa et al. 2003), J0402+379 (Rodriguez et al. 2006; Morganti et al. 2009a), and COSMOS J100043.15+020637.2 (Comerford et al. 2009b). In addition, a number of candidates for very close pairs of SMBHs have been reported, typically based on semi-periodic or other structures in radio jets

and in multi-wavelength light curves (e.g., Lobanov & Roland 2005; Valtonen et al. 2008; see Komossa 2006 for a review). In particular, a few galaxies with double-peaked [O III], and perhaps H$\beta$, emission lines have been presented as candidate binary AGNs, each AGN with its own narrow-line region (NLR; Zhou et al. 2004; Gerke et al. 2007; Comerford et al. 2009a). Double-peaked [O III] emission has also occasionally been observed in some nearby AGNs since the 1980s (e.g., Heckman et al. 1981; Whittle et al. 1988; Veilleux 1991a, 1991b), among them some that have all lines double-peaked. At that time, processes linked to radio(jet) activity had been suggested to explain these line profiles. Narrow-line splitting is also evident in a few compact radio sources (e.g., Holt et al. 2008).

In a search for peculiar emission-line AGNs in the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al. 2009), we have found SDSS J131642.90+175332.5 (SDSS J1316+1753 hereafter), which displays a rich system of narrow emission lines, all of which are double-peaked. In this Letter, we discuss this and other remarkable properties of this galaxy. We also critically examine a number of scenarios that can potentially explain the observed features including a close pair of unrelated AGNs, biconical outflows, jet–cloud interactions, special NLR geometries, and a binary or single AGN illuminating two NLRs in a galaxy merger. A cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ is used throughout.

## 2. SPECTRAL ANALYSIS

SDSS J1316+1753 is an emission-line galaxy at redshift $z = 0.15$, with an absolute magnitude $M_i = -21.9$ (calculated from the SDSS $i$_psf magnitude). The SDSS spectrum, corrected for Galactic extinction, is displayed in Figure 1(a), and a zoom on the H$\beta$–[O III] and H$\alpha$–[N II]–[S II] complex is shown in
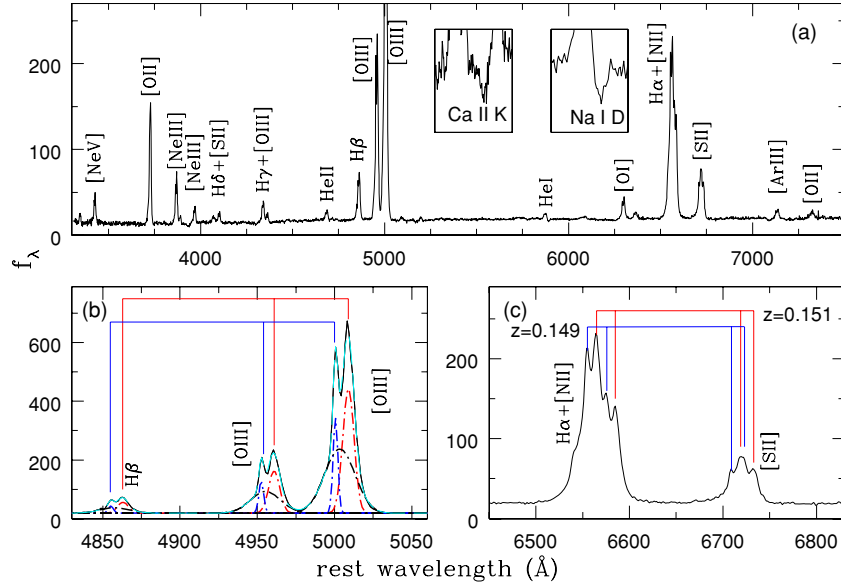
**Figure 1.** SDSS spectrum of SDSS J1316+1753. The upper panel shows the full spectrum, with emission lines labeled, and the insets show a zoom on the absorption features. The lower panel zooms into the [O III]–H$\beta$ and the H$\alpha$–[N II]–[S II] regime, and shows the two sets of narrow emission lines which are separated by 400–500 km s$^{-1}$ in velocity space. The red system is marked in red and the blue system in blue. The dot-dashed lines in the lower left panel represent our Gaussian fitting with two narrow lines (the red system and the blue system) and one intermediate broad component. The flux density $f_\lambda$ is given in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

**Table 1**
Emission-line Properties of SDSS J1316+1753

| Property | [Ne v] 3426 | [O II] 3727 | [Ne III] 3869 | H$\gamma$ | [O III] 4363 | He II 4686 | H$\beta$ | [O III] 5007 | [O I] 6300 | H$\alpha$ | [N II] 6583 | [S II] 6725 | [Ar III] 7136 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Blue system** | | | | | | | | | | | | | |
| Line ratio | 0.4 | 1.3 | 0.9 | 0.3 | 0.2 | 0.2 | 1.0[a] | 12.4 | 0.6 | 4.5 | 2.8 | 1.7[b] | 0.4 |
| $z$ | 0.1489 | 0.1492 | 0.1490 | 0.1491[c] | 0.1491[c] | 0.1491 | 0.1491 | 0.1491 | 0.1492 | 0.1491[c] | 0.1492[c] | 0.1492 | 0.1491 |
| FWHM[d] | 140 | 200 | 140 | 180[c] | 140[c] | 180[c] | 180 | 140 | 170 | 180[c] | 170[c] | 170 | 170 |
| **Red system** | | | | | | | | | | | | | |
| Line ratio | 0.7 | 1.9 | 1.1 | 0.4 | 0.2 | 0.2 | 1.0[a] | 13.9 | 0.4 | 4.0 | 2.5 | 2.1[b] | 0.3 |
| $z$ | 0.1509 | 0.1509 | 0.1509 | 0.1510[c] | 0.1510[c] | 0.1511 | 0.1510 | 0.1510 | 0.1510 | 0.1510[c] | 0.1509[c] | 0.1509 | 0.1510 |
| FWHM[d] | 630 | 430 | 500 | 430[c] | 480[c] | 430[c] | 430 | 480 | 290 | 430[c] | 400[c] | 400 | 450 |
| **Broad system** | | | | | | | | | | | | | |
| Line ratio | 0.3 | 2.1 | 0.7 | 0.5 | 0.1 | 0.2 | 1.0[a] | 10.4 | 0.7 | 5.1 | 3.0 | 1.9[b] | 0.2 |
| $z$ | 0.1494 | 0.1497 | 0.1497 | 0.1499[c] | 0.1498[c] | 0.1502 | 0.1499 | 0.1498 | 0.1502 | 0.1497 | 0.1497 | 0.1497 | 0.1499 |
| FWHM[d] | 1830 | 1150 | 1480 | 1380[c] | 1380[c] | 1380[c] | 1380 | 1380 | 1400 | 1390 | 1520 | 1340 | 1170 |

**Notes.**
[a] Normalized to 1.0. The observed flux of H$\beta$, in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$, is 1.2 (blue system), 3.2 (red system), and 6.0 (broad system).
[b] Sum of [S II] $\lambda$6716 and [S II] $\lambda$6731.
[c] Fixed.
[d] In units of km s$^{-1}$. Corrected for instrumental resolution.

Figures 1(b) and (c). Many emission lines are detected (Table 1), including the relatively rare feature of [Ar III] $\lambda$7136.

All emission lines show double-peaked profiles. Among each double peak, the emission-line system at lower redshift is hereafter referred to as "the blue system," and the system at higher redshift is referred to as "the red system." Close inspection of the strongest emission lines reveals the presence of an underlying broad component, which is clearly detected in [O III] $\lambda\lambda$4959, 5007, [O II] $\lambda$3727, [Ne III] $\lambda$3869 and in the Balmer lines H$\alpha$ and H$\beta$.

Emission lines were analyzed by fitting Gaussians, superposed on a local continuum. We use single Gaussian components to describe the narrow lines of the blue system and the red system, and one extra Gaussian component to model the broad

system. Fit parameters of all three Gaussians were the FWHM, flux, and central wavelength. Occasionally, for deblending or faint lines, we fixed the FWHM and central wavelength in the fitting process (see Table 1). All quoted FWHMs were corrected for the instrumental resolution. We have first focused on the brightest emission line, [O III] $\lambda$5007. The three-Gaussian parameterization describes the observed line profile well. The blue system and the red system are separated by $\sim$500 km s$^{-1}$ in velocity space. The blue [O III] line at $z = 0.1491$ is characterized by FWHM = 140 km s$^{-1}$, while the red line at $z = 0.1510$ shows FWHM = 480 km s$^{-1}$. The broad component peaks at a redshift $z = 0.1498$, intermediate between the two narrow lines, and has FWHM = 1380 km s$^{-1}$. Gaussians with similar widths and redshifts also successfully fit H$\beta$ and other
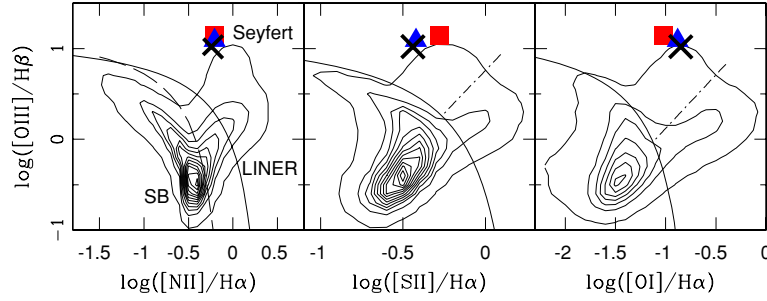
**Figure 2.** Location of the three emission-line systems in diagnostic diagrams. The red square refers to measurements of the red system, the blue triangle to the blue system, and the black cross to the broad component. The contours represent the distribution of SDSS narrow-line galaxies of Kauffmann et al. (2003). The single solid and dashed lines correspond to the dividing lines between AGNs and star-forming galaxies of Kewley et al. (2001) and Kauffmann et al. (2003), respectively. The dot-dashed line marks the dividing line between Seyferts and LINERs (Kewley et al. 2006). All three emission-line systems are located in the Seyfert regime.

emission lines (see Table 1). The emission-line strengths and ratios in the red system and the blue system are remarkably similar. Emission-line ratios place both systems in the AGN regime in diagnostic diagrams (Figure 2); the same holds for the broad component.

No broad component is detected in the Balmer lines—apart from the component at FWHM $\sim 1400$ km s$^{-1}$ already mentioned, which is similar to that seen in the other narrow lines, and therefore very likely has the same origin, different from a classical broad-line region (BLR). Faint absorption features from the host galaxy are visible in the spectrum, and we identify absorption features from Na I D and Ca II K. Measurements of higher signal-to-noise ratio (S/N) follow-up optical spectra would allow us to derive $\sigma_*$ directly from the absorption features.

We have checked the radio archives and found that SDSS J1316+1753 was detected in the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey at a flux level of $S_{\nu,\mathrm{NVSS}} = 10.3$ mJy and $S_{\nu,\mathrm{FIRST}} = 11.4$ mJy, respectively.

## 3. DISCUSSION

SDSS J1316+1753 is exceptional in showing double-peaked structure in all of its narrow emission lines plus an underlying broad component in most forbidden lines, likely peaking in between the two narrow systems. Given previous reports of spectroscopic binary AGN candidates (with double-peaked [O III], and perhaps H$\beta$), SDSS J1316+1753 suggests itself as another candidate which, in particular, has *all* of its emission lines double-peaked. However, line splitting of individual or all emission lines has also occasionally been observed before in single AGNs (e.g., Heckman et al. 1981; Veilleux 1991a, 1991b; Rodriguez-Ardila et al. 2006), and in a few compact radio sources (e.g., Holt et al. 2008). It has been suggested to be linked to the geometry of, or local physics in, the NLR, or the influence of radio jets. Therefore, other processes not related to binary AGNs can also be imagined which can explain the phenomenon of narrow double-peaked emitters. We discuss a large number of possibilities in turn. SDSS J1316+1753 with its rich, bright, and unusual emission-line spectrum allows us to test such models.

1. *Superposition of two unrelated, but spatially close, AGNs (a "dual" AGN).* This possibility is very unlikely for two reasons. First, the great similarity in the line fluxes and ratios, including the rare [Ar III] transition would then be pure coincidence. Second, and more seriously, the presence of a broad component that peaks at *intermediate* velocity in between the red system and the blue system is inconsistent with a chance projection.

2. *Outflow.* A biconical outflow could naturally produce double-peaked emission lines. However, in order to affect the whole NLR, including the low-ionization lines like [S II], an unusually powerful outflow would be required. Furthermore, a powerful outflow would likely produce a strong ionization and velocity stratification between the high-ionization lines that originate closer to the nucleus and the low-ionization lines at larger distances (e.g., Komossa et al. 2008). While an ionization stratification is apparent in the red system, there is none in the blue system.

3. *Jet–cloud interaction.* The local interaction of radio jets with NLR clouds is known to produce locally very complex [O III] profiles including broad components in radio galaxies (e.g., Whittle et al. 1988; Morganti et al. 2007; Holt et al. 2008). However, these processes are sometimes very localized, and do not usually dominate the integrated [O III] profile from the whole NLR (see also the discussion by Comerford et al. 2009a; but see Heckman et al. 1981; Veilleux 1991b). Nevertheless, we explore such a scenario for SDSS J1316+1753. Since no classical BLR is detected, SDSS J1316+1753 is of type 2, which in the context of the unified model of AGNs would imply an edge-on geometry with radiation cones and jets more likely perpendicular to our line of sight. A strictly perpendicular geometry would not produce double-peakedness, since the velocity component in our line of sight would be small. However, we could imagine intermediate viewing angles. Entraining the bulk of a classical NLR in a two-sided jet is not easy to achieve, since jet–cloud interaction usually produces cloud fragmentation rather than entrainment (see, e.g., the discussion by Komossa et al. 2008). Strictly localized interaction of the jet with a single cloud on each side of the nucleus might produce double-peaked lines and perhaps shock ionization, but in order for this profile to dominate the observed emission lines, the rest of the NLR would have to be weak or absent. We have measured the [O III] flux in the red system. Its luminosity of $3 \times 10^{42}$ erg s$^{-1}$ is typical for bright Seyfert galaxies or quasars, well above the emissivity expected from just two single NLR clouds. The high line luminosity we measure also argues against a scenario, in which we only observe the very inner NLR of SDSS J1316+1753 (line splitting in [O III] has occasionally been seen in the cores of AGNs; e.g., Mazzalay et al. 2009), the rest of the NLR being absent. Another variant of jet-induced line emission cannot be excluded. Young radio jets in gas-rich mergers are not uncommon, and their interaction with circumnuclear gas is known to produce complex emission-line profiles, including broad components (e.g.,

Holt et al. 2008; Inskip et al. 2008; see Morganti et al. 2009b for a review). Fast autoionizing shocks (Dopita & Sutherland 1996) might then also produce local ionizing continua which would be efficient in ionizing ambient gas, expanding around the jets.

4. *Special NLR geometry.* In purely geometrical terms, a spherical core component, plus a flat extended disk component seen from the side can naturally produce the red and the blue narrow systems together with the intermediate broad system. The broad component would arise in the spherical very inner part of the NLR (or outer BLR), the red system and the blue system in the disky part. The broad component would then, in terms of its FWHM, correspond to the outer BLR. However, the conditions in the outer BLR are not favorable to produce lines like [O II]. [O II] has low critical density, and is of relatively low ionization, while in the outer BLR, high density, and a higher degree of ionization would generally prevail. The red system and the blue system could plausibly arise in the classical NLR, if the NLR followed a strict disk geometry (e.g., Greene & Ho 2005), or followed the geometry of an inner bar or an inner two-sided spiral. An attractive feature of this scenario is that it is consistent with the great similarity of the line ratios in the red system and the blue system (including the detection of [Ar III] in both of them), because only a single ionizing continuum is needed, and because the physical condition in the NLR on both sides would be expected to be similar (in terms of metal abundances, cloud densities, and column densities).

If emission-line ratios are dominated by photoionization, we can use the ratio of [O II]/[O III] to estimate the ionization parameter (Komossa & Schulz 1997). We find $\log U \simeq -2$ for the red system and the blue system, assuming that the density we measure from the [S II] ratio ($n_e \approx 30$ cm$^{-3}$ for the blue system and $n_e \approx 400$ cm$^{-3}$ for the red system) reflects the average density of the system and that there are no large density inhomogeneities, and without performing any extinction correction. The measured total H$\beta$ luminosity implies a minimum rate $Q$ of hydrogen-ionizing photons of $Q = 2.7 \times 10^{54}$ s$^{-1}$ (assuming unity covering fraction of the H$\beta$ emitting clouds), which then translates into a *lower limit* on the distance of the NLR of 0.4 kpc of the red system and 1.6 kpc of the blue system.

5. *A galaxy merger with one (or two) active nuclei.* In this scenario, SDSS J1316+1753 would consist of two galaxies with two separate NLRs in the process of merging. The SDSS image of SDSS J1316+1753 indeed indicates a possibly distorted morphology and an excess of companion galaxies.[3] In a merger scenario, we can have either two (obscured) accreting black holes each illuminating its own NLR (the scenario was favored previously to explain some [O III] double-peaked emitters), or else a single AGN illuminating the interstellar media of both galaxies, i.e., both NLRs. The similarity in line fluxes and ratios of the red system and the blue system argues for a relatively small separation of the two NLRs, no matter whether both of them

see the ionizing continua of one, or of two AGNs. Receiving similar ionizing continua would potentially make line ratios more similar.

In the merger scenario, we expect that the host galaxy absorption features should more closely match the redshift of the emission lines from the more massive host galaxy (while in jet/outflow-related scenarios the host redshift should be in between the two emission-line redshifts). We do detect faint absorption features from the host galaxy in the spectrum of SDSS J1316+1753. By comparing the observed peak location of the two absorption features with the redshifts of the red system and the blue system, we tentatively find that they are either more consistent with the red system, or are located in between the two emission systems. In the context of the merger scenario, the *broad* component of the forbidden lines may arise in gas that is related to starburst-driven superwinds. Mergers frequently trigger enhanced starburst activity, and the well-known merger and binary AGN NGC 6240 does show off-nuclear broad Balmer lines which are likely linked to superwinds (Heckman et al. 1990). If the two narrow [O III] systems represented two classical NLRs of the two merging galaxies, we could use their widths as a proxy for gaseous velocity dispersion (e.g., Nelson 2000). Actually doing so, and assuming the $M_{BH}$–$\sigma$ relation to apply (Ferrarese & Ford 2005), we obtain black hole masses of $2 \times 10^8$ $M_\odot$ and $5 \times 10^5$ $M_\odot$; the second value is very low and would then imply a minor merger.

## 4. FUTURE OBSERVATIONS

A number of future observations can distinguish between different scenarios for SDSS J1316+1753 and double-peaked narrow-line emitters in general. These would either focus on follow-ups of SDSS J1316+1753, or would address class properties of larger samples systematically selected from SDSS. *Hubble Space Telescope* imaging and Space Telescope Imaging Spectrograph spectroscopy will reveal the detailed morphology of the host galaxy of SDSS J1316+1753 and will determine or constrain the extents and loci of the red, the blue, and the broad intermediate systems. High-resolution radio imaging might reveal the presence of jets, and/or provide evidence for two active nuclei, if present. While detailed emission-line analysis and modeling of individual objects likely holds the key to understanding the physical processes involved, a systematic search for similar objects in the SDSS data base (H. Lu et al. 2010, in preparation) to study the bulk properties of double-peaked emitters is important, too. Measurements of the host absorption features in spectra of high S/N will show whether the absorption features coincide in redshift with one of the two narrow emission-line systems, or are always located in between. The question of whether one AGN in a merger scenario is sufficient to illuminate both NLRs, or two AGNs are required, can be addressed by searching for ionization stratifications in the narrow lines, in cases where high-resolution imaging is not available. If only one AGN is illuminating two NLRs, the second NLR should lack an ionization stratification. Of great interest will be the frequency of double-peaked emitters in type 2 versus type 1 AGNs, and in high-luminosity AGNs (quasars) versus low-luminosity systems (Seyfert galaxies). If they are more abundant in type 2 AGNs, that would hint at geometrical effects playing a role. If they are more abundant in quasars than in Seyferts, that would be consistent with a merger scenario, since quasars are likely powered by major mergers.

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[3]  The velocity between the red system and the blue system ($\sim$400–500 km s$^{-1}$) is rather high, above that typically expected for a bound merger. Previously reported double-peaked emitters had peak separations of 730 km s$^{-1}$ and 630 km s$^{-1}$, respectively (Zhou et al. 2004; Gerke et al. 2007). Systematic shifts of single-peaked emission lines with respect to host absorption lines observed by Comerford et al. (2009a) are on the order of 100–300 km s$^{-1}$.

In summary, a galaxy merger with two (or one) AGNs illuminating the NLRs of the two merging galaxies is one possible scenario to explain narrow double-peaked emitters, especially SDSS J1316+1753 because not just one but all emission lines are double-peaked, and an additional broad component in forbidden lines is present at intermediate velocity. However, the line separation of the red and the blue narrow systems of about 400–500 km s$^{-1}$ is relatively large for a bound merger; and the remarkable similarity in line fluxes and ratios of the red system and the blue system needs to be explained. While localized jet–cloud interaction in an otherwise gas-poor NLR is unlikely because of the high observed emissivity in the emission lines, newly triggered jets in a gas-rich merger, and special NLR geometries remain plausible possibilities. Confirming or rejecting the binary AGN hypothesis is of great interest in the context of studying BH mergers, mechanisms of fueling and gas transport into the galaxy core, and/or to learn more about NLR dynamics and geometry. SDSS J1316+1753 might be a Rosetta stone in this regard, due to its rich and very bright narrow-line spectrum and the presence of the remarkable broad component in the forbidden lines.

*Note added after submission.* After submission of our manuscript, two more papers on double-peaked emitters selected from the SDSS appeared in preprint form (Smith et al. 2009; and Liu et al. 2009). These two, and a preprint by Wang et al. which we received, are complementary to ours in that they study sample properties of narrow double-peaked emitters in type 1 and type 2 AGNs, while our work focuses in detail on the emission-line properties of a single object.

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