**HST and LAMOST discover a dual active galactic nucleus in J0038+4128**

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Accepted 2014 January 17. Received 2014 January 16; in original form 2013 October 14

**ABSTRACT**

We report the discovery of a kiloparsec-scale dual active galactic nucleus (AGN) in J0038+4128. From the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) images, we find two optical nuclei with a projection separation of 4.7 kpc (3.44 arcsec). The southern component (J0038+4128S) is spectroscopically observed with the HST Goddard High Resolution Spectrograph in the UV range and is found to be a Seyfert 1 galaxy with a broad Lyα emission line. The northern component (J0038+4128N) is spectroscopically observed during the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (also named the Guoshoujing Telescope) pilot survey in the optical range. The observed line ratios as well as the consistency of redshift of the nucleus emission lines and the host galaxy’s absorption lines indicate that J0038+4128N is a Seyfert 2 galaxy with narrow lines only. These results thus confirm that J0038+4128 is a Seyfert 1–Seyfert 2 AGN pair. The HST WFPC2 F336W/U-band image of J0038+4128 also reveals for the first time for a dual AGN system two pairs of bi-symmetric arms, as are expected from the numerical simulations of such system. Being one of a few confirmed kiloparsec-scale dual AGNs exhibiting a clear morphological structure of the host galaxies, J0038+4128 provides a unique opportunity to study the co-evolution of the host galaxies and their central supermassive black holes undergoing a merging process.

**Key words:** galaxies: active – galaxies: individual: J0038+4128 – galaxies: interactions – galaxies: nuclei – galaxies: Seyfert.

**1 INTRODUCTION**

In the hierarchical Λ cold dark matter (ΛCDM) cosmology, galaxies built up via mergers (Toomre & Toomre 1972). Binary supermassive black holes (SMBHs) are natural outcomes of galaxy mergers (Begelman, Blandford & Rees 1980; Milosavljević & Merritt 2001; Yu 2002), since almost all massive galaxies are believed to host a central SMBH. In the gas-rich case, the strong tidal interactions caused by galaxy mergers can trigger the active galactic nucleus (AGN) by sending a large amount of gas to the central regions (Hernquist 1989; Kauffmann & Haehnelt 2000; Hopkins et al. 2008). A dual AGN could emerge if the two merging SMBHs are both simultaneously accreting gas in a gas-rich major merger. Finding dual AGNs, especially those exhibiting two black holes on a kiloparsec scale (Liu et al. 2013), will provide important clues to understand the relation between the AGN activity and the galaxy evolution and AGN physics (Colpi & Dotti 2011; Yu et al. 2011). Over the past few years, hundreds of dual AGNs of separations greater than 10 kpc have been discovered (e.g. Myers et al. 2007, 2008; Green et al. 2010; Piconcelli et al. 2010). However, such systems represent only the earliest stage of the binary SMBH evolution. No more than dozens of close dual AGNs (separations between 1 and 10 kpc) are found both from either systematic searches (e.g. Liu et al. 2010, 2013; Rosario et al. 2011) or by serendipitous discoveries (e.g. Junkkarinen et al. 2001; Komossa et al. 2003; Ballo et al. 2004; Bianchi et al. 2008; Fu et al. 2011; Koss et al. 2011; McGurk et al. 2011). However, most of them only show two prominent nuclei either in the radio, X-ray or the optical band, the properties of the host galaxies are poorly known. The latter are extremely important for probing the relation between the galaxy evolution and nucleus activity (Shields et al. 2012).

Here, we report the discovery of a new dual AGN in J0038+4128 (z = 0.0725) with a spatial separation of 4.7 kpc (3.44 arcsec). A
2 OBSERVATIONS AND REDUCTIONS

2.1 HST images and spectra

The images presented here were obtained with the WFPC2 on board the Hubble Space Telescope (HST) as part of the General Observer (GO) programme GO-6749 (PI: Laura Danly) on 1996 August 27. WFPC2 contains four Loral CCD detectors of 800 × 800 pixels. The field of view (FOV) of the Planetary Camera is about 34 × 34 arcsec$^2$ (0.046 arcsec pixel$^{-1}$), whereas that of each of the three Wide Field (WF) arrays is 150 × 150 arcsec$^2$ (0.1 arcsec pixel$^{-1}$). Fig. 1 shows the WFPC2 combined images of J0043+4128 located in one of the three WFs of two deep exposures (600 s) in the F336W/U-band and two deep exposures (400 s) and one shallow exposure (30 s) in the F555W/V-band. The combined images were produced at the Canadian Astronomical Data Center (CADC) with MULTIDRIZZLE

with improved astrometry and geometric distortions correction.\footnote{Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA).} J0038+4128 is well resolved into two components, a main (S) and a companion (N), separated by 3.44 arcsec in both bands.

The UV spectrum of J0038+4128S was obtained with the HST Goddard High Resolution Spectrograph (GIRS) on 1997 Febru-
ary 4, also under project GO-6749. Six exposures were taken with the G140L grating through the Large Science Aperture (2.0 arcsec × 2.0 arcsec) for a total integration time of 18 822 s. The resolving power is about 1000 at 1200 Å, which corresponds to ∼300 km s$^{-1}$. The spectra were processed using the standard CALHRS v1.3.14 reduction pipeline with the latest reference files. We compute the wavelength zero-points of the spectra with the nearest SPYBAL\footnote{http://hla.stsci.edu/} calibration spectrum observations in time using the STSDAS IRAF task waveoff and find offsets ranging from 0.6956 to 0.9948 Å for individual exposures. After correcting for the wavelength zero-points for each exposure, we present the final combined spectrum in Fig. 2. The spectrum was rebinned to a common wavelength grid with a constant step size of 0.57 Å.

2.2 LAMOST spectra

The optical spectrum of J0038+4128N were observed during the LAMOST pilot survey on 2011 October 5. LAMOST is a 4 metre quasi-meridional reflecting Schmidt telescope equipped with 4000 fibres, each of an angular diameter of 3.3 arcsec projected on the sky, in an FOV of 5° in diameter (Cui et al. 2012). The spectra has a resolution of $R \sim 1800$ and covers wavelengths from 3700 to 9000 Å. In addition to J0038+4128N, LAMOST also observed a region a few arcsec east of the two nuclei marked as J0038+4128H shown in Fig. 1 on 2011 October 24 and 28. The weather of the three nights was clear but of relatively poor seeing (∼3 arcsec). Long-term monitoring of the LAMOST fibre positioning accuracy (Yuan et al., in preparation) shows that it varies from fibre to fibre. However, the observations of J0038+4128N and J0038+4128H were obtained with fibres of the highest precision (better than 0.5 arcsec). The data were processed using the LAMOST standard pipeline, with flux calibration better than ∼10 per cent (Liu et al. 2013).

We summarize the details of all spectral observations of J0038+4128 in Table 1, including the three positions of the observed regions, central positions of aperture, telescopes used, observational dates, seeing, total exposure times, spectral coverage and resolving power. In addition, the photometric properties of J0038+4128 from archival observations are summarized in Table 2.

3 RESULTS AND DISCUSSIONS

3.1 Confirmation of a dual AGN

Fig. 1 (cf. also Section 3.4) shows clear evidence of interaction between the two components and the chance of the system being a coincidental superposition of two physically unrelated objects or the possibility of being a gravitationally lensed system can both be squarely ruled out. However, images alone are insufficient to distinguish starbursts from AGNs of types 1 or 2. With the spectra obtained from the HST and LAMOST, we can constrain the nature of the two components of J0038+4128 by examining the widths of observed emission lines as well as the locations of the measured line

\cite{1996ApJ...464L..27P}
Figure 2. Top: the UV spectrum of J0038+4128S obtained with the HST/GHRS using the G140L grating. Bottom: LAMOST spectra of J0038+4128N (black) and of J0038+4128H (red and blue). Detected emission lines as well as absorption lines are labelled for J0038+4128S. For J0038+4128N and J0038+4128H, emission lines detected as well as the atmospheric (A and B bands) are marked. In addition, two absorption lines of neutral iron from the host galaxy have been well detected in the spectrum of J0038+4128N. Most other absorption line-like features are artefacts produced by poor sky extraction.

Table 1. Observation.

| Area       | RA        | Dec.       | Facility | Date       | Seeing (arcsec) | Exp. time (second) | Spectral coverage (Å) | Resolving power |
|------------|-----------|------------|----------|------------|-----------------|---------------------|----------------------|-----------------|
| Yellow circle | 00 38 33.05 | +41 28 53.48 | LAMOST | 2011 Oct 05 | 4.0             | 1800                | 3700–9000             | 1800            |
| Red circle | 00 38 33.36 | +41 28 51.95 | LAMOST | 2011 Oct 24 | 3.4             | 3600                | 3700–9000             | 1800            |
| Red circle | 00 38 33.36 | +41 28 51.95 | LAMOST | 2011 Oct 28 | 2.8             | 2100                | 3700–9000             | 1800            |
| Yellow box | 00 38 33.12 | +41 28 50.30 | HST/GHRS | 1997 Feb 04 | –               | 18 822              | 1275–1561             | 1000            |

Table 2. Photometric data for J0038+4128.

| Band   | λ (µm) | J0038+418S | J0038+418N | Facility |
|--------|--------|------------|------------|----------|
| FUV    | 0.16   | 19.041 ± 0.136 | GALEX     |
| NUV    | 0.23   | 18.469 ± 0.072 | GALEX     |
| ν′     | 0.36   | 16.889 ± 0.015 | 24.635 ± 0.975 | SDSS     |
| ν″     | 0.47   | 15.604 ± 0.003 | 19.985 ± 0.020 | SDSS     |
| ν′′′   | 0.62   | 14.831 ± 0.003 | 18.752 ± 0.011 | SDSS     |
| ν‴    | 0.75   | 14.261 ± 0.003 | 18.386 ± 0.012 | SDSS     |
| ν‴‴   | 0.89   | 13.943 ± 0.005 | 18.004 ± 0.023 | SDSS     |
| 3ν‴‴ | 1.25   | 13.286 ± 0.048 | 2MASS     |
| Hν″‴ | 1.65   | 12.556 ± 0.070 | 2MASS     |
| Kν‴‴ | 2.17   | 12.103 ± 0.074 | 2MASS     |
| W1     | 3.40   | 11.624 ± 0.023 | WISE      |
| W2     | 4.60   | 11.070 ± 0.020 | WISE      |
| W3     | 12.00  | 8.291 ± 0.019  | WISE      |
| W4     | 22.00  | 5.636 ± 0.033  | WISE      |

Notes. The two nuclei just can be separated in SDSS images, we list magnitudes from SDSS for both components and total magnitudes from other bands for the whole system.

*SDSS model magnitude.

**Magnitudes are for isophotal fiducial elliptical-aperture.

flux ratios on the line-ratio diagnostic diagrams (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987; Kewley et al. 2001, 2006; Kauffmann et al. 2003). Fig. 2 shows the HST UV spectrum of J0038+4128S, which clearly exhibits broad emission features identified as H I Lyα and the Si iv λλ1394,1403 lines. Since Lyα and the N v doublet (λλ1239,1243) are blended, we fit the observed profile by the sum of two pairs of two Gaussian, one broad and one narrow, with one pair for Lyα and the other for the N v doublet. When fitting, data points corresponding to most prominent absorption features are masked and excluded from the fitting. The fitting yields a full width at half-maximum (FWHM) for the broad component of Lyα of 4700 ± 70 km s⁻¹, indicating J0038+4128S harbors a Seyfert 1 type nucleus. Furthermore, a close examination of the UV spectra reveals absorption lines that are seen among ~50 per cent Seyfert 1 galaxies (Crenshaw et al. 1999; Dunn et al. 2007).

J0038+4128N is clearly not a type 1 AGN since the optical spectrum obtained with the LAMOST reveals only narrow emission lines. Its nature, whether it is a Seyfert 2, a starburst, or a composite of both can be established by examining the locations of the diagnostic line ratios [O ii] λλ5008/Hβ versus [N ii] λ6585/Hα, [S ii] λλ6718,6731/Hα and [O ii] λλ3726,3729/Hα on the line-ratio diagnostic diagrams. We measure line fluxes by fitting Gaussians to profiles of detected emission lines, plus a first- or second-order polynomial for the continuum. From the measured Balmer decrement, we estimate a colour excess E(B−V) = 0.71 for J0038+4128N, a value consistent with the expectation for Seyfert 2 galaxy. The
extinction corrected (for both the host and the foreground Galactic extinction) line ratios of J0038+4128N (Fig. 3) show clearly that it is a Seyfert-type galaxy. We use the diagnostic doublet line ratio of [S ii]λ6718/6731, assuming a typical electron temperature of 10^4 K, to estimate the electron density n_e of the narrow-line region of J0038+4128N. The result log n_e/cm^-3 ~ 2.5 is consistent with typical values found for narrow-line regions of Seyfert galaxies. However, it is still ambiguous whether the gas of the narrow-line region in J0038+4128N is ionized by nuclear emission from J0038+4128S or by that from J0038+4128N itself. The host galaxy spectrum of J0038+4128N is seen clearly in Fig. 2, with the Fe ii λ5268 and the Fe ii λ5617 lines well detected. The redshift derived from the Fe ii λ5617 line of the host galaxy is 0.073 ± 0.000 11, consistent with the value derived from the narrow emission lines of J0038+4128N (see Section 3.2). The signal-to-noise ratio of the spectrum of the host galaxy taken at J0038+4128H with the LAMOST is unfortunately too low to see the underlying absorption features, let alone measurement of the Fe ii lines. Nevertheless, the consistency in redshift of emission lines from the ionized gas and absorption lines from the host galaxy strongly supports that the gas around the nuclear region of J0038+4128N is ionized locally. In other words, there are two ionized sources, J0038+4128S and J0038+4128N.

On the other hand, we used Yunnan Faint Object Spectrograph and Camera on Yunnan 2.4 m telescope (pixel size 0.283 arcsec) to obtain the long-slit medium resolution (R ~ 2200, λ = 4970–9830 Å) spectra of J0038+4128 on 2013 November 10. With clear sky condition and ~ 1.0 arcsec seeing, the J0038+4128S and J0038+4128N are spatially resolved as shown in Fig. 4, which confirms that J0038+4128S is a Seyfert 1 galaxy revealed by the HST UV spectrum and J0038+4128N is a Seyfert 2 galaxy revealed by the LAMOST optical spectrum.

In addition, the diagnostic line ratios of J0038+4128H are presented in Fig. 3 and the results also suggest that J0038+4128H is consistent with AGN ionization. The classical size of a narrow-line region of Seyfert 1 galaxy is about 1–2 kpc (e.g. Bennert et al. 2006) and corresponding to 1.3–2.7 arcsec in J0038+4128. Considering the small 2.8 arcsec distance between the centre of the aperture towards J0038+4128H and J0038+4128S core and the high seeing, the spectra taken at J0038+4128H may mainly come from the narrow-line region of J0038+4128S. That is why the measured line ratios at J0038+4128H are consistent with AGN ionization. But it is a little strange that the J0038+4128H and J0038+4128N share the similar ionization conditions as shown in Fig. 3. Future optical integral-field or long-slit spectroscopy of high spatial resolution are needed to reveal the ionization conditions for the whole system.

In summary, the existing data, both imaging and spectroscopy, strongly suggest that J0038+4128 is a Seyfert 1–Seyfert 2 AGN pair.

3.2 Radio and X-ray properties of J0038+4128
J0038+4128 is detected (but unresolved) at 1.4 GHz by the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and at 325 MHz in a radio survey of M31 (Gelfand, Lazio & Gaensler 2004), with an integrated flux of 5.2 ± 0.4 mJy and 8.3 ± 0.72 mJy, respectively. The radio spectral index α (Fα ~ ν^-α) is about 0.32, and indicates that J0038+4128 is a compact radio source. The rest frame radio luminosity at 5 GHz is estimated at 2.12 × 10^{38} erg s^-1, assuming the above power-law spectral index. The rest-frame B-band luminosity is about 5.17 × 10^{43} erg s^-1 estimated from the SDSS u and g magnitudes by the equation of Vanden Berk et al. (2001).

The radio and optical luminosities thus place J0038+4128 as a typical Seyfert galaxy (Sikora, Stawarz & Lasota 2007). J0038+4128 has also been detected in the XMM–Newton slew survey (Saxton et al. 2008). The survey yields two X-ray sources close to J0038+4128. Of the two sources, the one with the larger position offset has parameter Ver_Pusp set to true which means that its position is poorly constrained. Thus, we have adopted measurements of the X-ray source closest to J0038+4128S (with an offset of only 2.1 arcsec from J0038+4128S). The source has an X-ray flux of (1.3 ± 0.31) × 10^{-11} erg cm^-2 s^-1 at band 0 (0.2–12 keV) and (4.6 ± 1.1) × 10^{-12} erg cm^-2 s^-1 band 5 (0.2–2 keV), and is not detected at band 4 (2–12 keV). Given a Galactic absorption value of NH = 4.4 × 10^{20} cm^-2, estimated from E(B–V) = 0.069, using the relation of Predehl & Schmitt (1995), we find an X-ray luminosity L_{0.5–10keV} ~ 1.5 × 10^{44} erg s^-1 for a photon index Γ = 1.8. The above X-ray luminosity and the rest-frame B-band absolute magnitude M_B = −20.5 also show that J0038+4128 is a Seyfert-type galaxy (Brusa et al. 2007).

6 We modelled the SDSS u- and g-band images of J0038+4128 using the galaxy structure fitting code GAFFT v3.0 (Peng et al. 2002) by two Gaussian profiles for the dual AGN and a Sérsic component for the extended host galaxy.

7 WebPIMMS: http://heasarc.nasa.gov/Tools/w3pimms.html
3.3 Relative line-of-sight velocity of the dual AGN

For J0038+4128N, we measured the redshift by fitting Gaussian profiles to emission lines detected in the LAMOST red arm spectra only (5800–9000 Å), given the higher accuracy of wavelength calibration of the red arm spectra compared to those of the blue arm (3700–6000 Å). By fitting the [N II] λλ6550,6585, Hα and the [S II] λλ6718,6733, we derive an average redshift of $z_N = 0.07328 \pm 0.00014$ for J0038+4128N. For J0038+4128S, only the broad Lyα can be fitted reliably (the N v and Si iv lines are too weak to obtain reliable redshifts). The measured central wavelengths of the broad and narrow components are not the same, which is normal since in most AGNs the Lyα emission line shows an asymmetric profile. The broad component yields a redshift of $0.07330 \pm 0.00030$. However, from the UV spectrum plotted in Fig. 2, we find that the narrow component is closer to the overall centroid of the whole Lyα profile, thus adopt the redshift $z_S = 0.07177 \pm 0.00015$ of narrow component of Lyα as the system value of J0038+4128S. The value is also consistent with the estimate of Barbiere & Romano (1976). From $z_N$ and $z_S$, we find that the dual AGN nuclei have a relative line-of-sight velocity of $453 \pm 87$ km s$^{-1}$.

3.4 Host galaxy morphology

With the high spatial resolution images provided by the HST, the morphology and structure of J0038+4128 can be studied in detail. In the F336W/U-band image, which reveals the star-forming activities, two pairs of bi-symmetric spiral arms are detected in a binary AGN system for the first time. The results are consistent with the numerical simulations of Di Matteo, Springel & Hernquist (2005). They have simulated the merging of two disc galaxies of the size of the Milky Way and found the tidal interactions can distort the discs into a pair of bi-symmetric spirals as the two galaxies begin to coalesce. In addition to the bi-symmetric spiral arms, there are several compact knots scattered around the two nuclei. Knots triggered by interaction are common features in merging galaxies (Villar-Martín et al. 2011). The ongoing process of star formation in those knots can be confirmed by further spectroscopy. In the F555W/V-band image, we see a stream-like substructure along the north-western edge. This may indicate that the two galaxies may have encountered more than once.

3.5 Variability in the optical and infrared bands

J0038+4128 is found to be a fast variable in the optical, as shown by Barbiere & Romano (1976). They detect irregular variations of large amplitudes (~1.5 mag) on short time-scales (few days) in B band based on hundreds of measurements accumulated with the 67/92 cm Schmidt Telescope of Asiago and the 182 cm Telescope of Cima Ekar from 1965 September 5 to 1975 January 13. The strong, fast optical variability indicates the presence of a fast flare component (tens of days) in the light curve of J0038+4128.

Finally, J0038+4128 is also detected by the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) in all bands. WISE maps the entire sky at 3.4, 4.6, 12 and 22 μm (bands W1, W2, W3 and W4, respectively) at an angular resolution of 6.1, 6.4, 6.5 and 12.0 arcsec, respectively. In the WISE All-Sky Data Release Source Catalog, a variability flag (of integer values 0–9), var flags, is assigned to every detected object in each band, indicating the probability of possible flux variations. The greater the value of var flags, the higher the possibility of variability (see Hoffman et al. 2012 for detail). For J0038+4128, the flag has the highest value of 9 in both W1 and W2 bands and the light curves in the two bands show variability of amplitude of about 0.15 mag over a time-scale of half year.

4 SUMMARY

J0038+4128 is resolved to contain two compact nuclei in both F336W/U- and F555W/V-band images secured with the HST WFPC2. The HST GHRS UV spectrum of the southern nucleus shows broad Lyα emission (FWHM ~ 4700 km s$^{-1}$), which indicates that it is a Seyfert 1 galaxy. The LAMOST optical spectrum of the northern nucleus shows narrow emission lines only. Line diagnostics as well as the consistency in redshift between emission lines from the ionized gas and absorption lines from the host galaxy suggest it is a Seyfert 2. Therefore, the HST and LAMOST data confirm that J0038+4128 is a Seyfert 1-Seyfert 2 AGN pair with a projected spatial separation of 4.7 kpc (3.4 arcsec) and a line-of-sight relative velocity of 453 km s$^{-1}$.

The F336W/U-band image of J0038+4128, also reveals for the first time for a dual AGN system two pairs of bi-symmetric spiral arms. The HST images also reveal a number of compact star-forming knots as well as some tidal stream features.

Future optical integral-field spectroscopy of high spatial resolution would be extremely useful for further study of J0038+4128, in order to reveal the physical conditions and chemical properties of both the nuclear ionized gas and gas of the host galaxy for the whole entire system. Such a study will provide us much needed information of the co-evolution of the host galaxy and the central black holes.

ACKNOWLEDGEMENTS

This work is supported by National Key Basic Research Program of China 2014CB845700. We thank Professor Fukun Liu and Dr Andreas Schulze for providing valuable comments and suggestions of this paper.

This work has made use of data products from the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST), Sloan Digital Sky Survey (SDSS), Galaxy Evolution Explorer (GALEX), Two Micron All Sky Survey (2MASS), Wide-field Infrared Survey Explorer (WISE), NRAO VLA Sky Survey (NVSS), XMM-Newton and Yunnan 2.4 m telescope.

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MNRAS 439, 2927–2932 (2014)
