LETTER TO THE EDITOR

Finding binary active galactic nuclei candidates by the centroid shift in imaging surveys

II. Testing the method with SDSS J233635.75-010733.7

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ABSTRACT

In Liu (2015), we propose selecting binary active galactic nuclei (AGNs) candidates using the centroid shift of the images, which is induced by the non-synchronous variations of the two nuclei. In this paper, a known binary AGN (SDSS J233635.75-010733.7) is employed to verify the ability of this method. Using 162 exposures in the R band of Palomar Transient Factory (PTF), an excess of dispersion in the positional distribution of the binary AGN is detected, though the two nuclei cannot be resolved in the images of PTF. We also propose a new method to compare the position of the binary AGN in PTF g and R band and find the difference is highly significant even only with 20 exposures. This new method is efficient for two nuclei with different spectral energy distributions, e.g., type I + type II AGN or off-set AGN. Large-scale surveys, e.g., the Panoramic Survey Telescope and Rapid Response System and the Large Synoptic Survey Telescope, are expected to discover a large sample of binary AGN candidates with these methods.

Key words. Galaxies: active – Astrometry – Methods: data analysis

1. Introduction

Supermassive black holes (SMBHs) are discovered in the majority of massive galaxies (Kormendy & Richstone 1995). They should have grown through mergers and gas accretion (Volonteri et al. 2003; Di Matteo et al. 2008; Kormendy & Ho 2013). Thus, binary active galactic nuclei (AGNs) [1] are expected to be common, since galaxy mergers can trigger the activity of SMBHs (Begelman et al. 1980; Hernquist 1989; Kauffmann & Haehnelt 2000; Hopkins et al. 2008). Although hundreds of binary AGNs are found with separations of tens of kiloparsec (kpc), only about ten binary AGNs are known with separations ∼10 kpc (Junkkarinen et al. 2001; Komossa et al. 2003; Hennawi et al. 2006; Fu et al. 2011; Koss et al. 2011; Mazzarella et al. 2012; Liu et al. 2013; Müller-Sánchez et al. 2015). The occurrence rate of kpc-scale binary AGNs (−1%) is lower than the expected value by a factor of ten if each major merger can induce a binary AGN (Yu et al. 2011). Non-simultaneous activity and the gas content of galaxies are invoked to reconcile this apparent discrepancy (Foreman et al. 2009; Yu et al. 2011; Van Wassenhove et al. 2012).

On the observational aspect, a large and complete sample is important for the assessment of this discrepancy. Serendipitously discovered binary AGNs are rare and not sufficient to build a statistically meaningful sample. A systematic method is required for identifying kpc-scale binary AGN candidates. Double-peaked narrow lines (e.g., double-peaked [O III] lines) have been utilized to select kpc-scale binary AGNs (Wang et al. 2009; Liu et al. 2010; Smith et al. 2010; Shen et al. 2011). However, double-peaked narrow lines are usually produced by the gas dynamics (Fu et al. 2012; Blecha et al. 2013; Müller-Sánchez et al. 2015). Moreover, the line shift of a binary AGN in a face-on orbit is small and undetectable. Therefore, an efficient method is needed to well complement spectroscopy methods.

In Liu (2015, hereafter Paper I), we show that the imaging centroid of a binary AGN will shift due to the non-synchronous variation of the two nuclei. Thus, such binary AGNs can be revealed by multi-epoch observations, even if the separation is smaller than the angular resolution. This method utilizes the violent variation of AGNs; thus, it is more suitable for two type I AGNs or blazars with strong variability and its efficiency is low for type I + type II binaries. Therefore, we still need an efficient method for the pairs including type II AGN or a galactic nucleus without an AGN. The continuum of type I AGN is bluer than type II AGN or a galactic nucleus without an AGN, which is another distinguishable property of AGNs that can be used to uncover binary AGNs. If the spectral energy distributions (SEDs) of two nuclei are significantly different and two or more filters are available, the images of the blue and red filter are more dominated by the bluer and redder nucleus respectively. As a result, the centroid of the binary in the blue (red) filter should shift towards the bluer (redder) nucleus compared with the centroid in the red (blue) filter. This new method should be valid for two nuclei with different SEDs, e.g., type I + type II AGN, type I AGN+ broad absorption line (BAL) quasar, and type I AGN + galaxy (offset AGN). It is also appropriate to two type II nuclei if the colors of the two host galaxies are remarkably different. As we mentioned in Paper I, the fast variation in jet or the reflection from a cloud near a single AGN can mimic another “nuclei”

[1] In this paper, binary AGNs generally stand for any double sources discovered by imaging or spectroscopy. We do not strictly distinguish binary AGNs from dual AGNs or AGN pairs.
in the image and thus contaminates the candidates selected by the centroid shift. Follow-up high resolution imaging and spectroscopy are still required to confirm the candidates. Therefore, before hunting for new binary AGNs, we would like to select a known binary AGN to verify the two methods.

In Sect. 2, we describe the target and data selection. In Sect. 3, the procedure for calculation of the centroid in one band is explained. In Sect. 4, the result of the centroid shift between two bands is shown. In Sect. 5, we discuss the implications of the results and present our conclusions.

2. Target and Data Selection

Since more than 100 exposures are required by the method proposed in paper I, the *Palomar Transient Factory* (PTF), with a large sky coverage and frequent exposures, is selected to test our methods. There are three criteria employed to select a known binary AGN covered by PTF: (1) there is at least one type I nucleus in the binary; (2) the two nuclei are not resolved in PTF images; (3) there are more than 100 exposures to ensure the significance. As a result, only one source, SDSS J233635.75-010733.7, is found to be suitable for testing our method. This source is discovered by an infrared imaging survey at the Keck Observatory and confirmed to be a binary quasar (a standard quasar with a blue continuum and broad emission lines and a BAL quasar) by resolved optical spectra (Gregg et al. 2002). The separation of the two quasars is 1.67″, while the mean seeing of PTF observations is 2.1″ and 2.2″ in R and g band, respectively. The pixel scale of PTF CCD is 1.01″ (Law et al. 2009). Thus, the two quasars cannot be resolved in the image of PTF (Figure 1), though the source slightly deviates from the point spread function (PSF). PTF observed this source 162 and 103 times at R and g band, respectively. As a result, this source is appropriate for the test on the centroid method.

3. Centroid Shift in R band

We present a realistic procedure for the method proposed in Paper I in this section for the R band exposures of SDSS J233635.75-010733.7.

The centroids in pixel units of all sources in the 162 R band exposures were calculated by SExtractor. The sources with a significance higher than 3σ in at least 4 adjacent pixels were extracted. The windowed centroids, XWIN_IMAGE and YWIN_IMAGE, were adopted to achieve the accuracy close to the theoretical limit set by image noise. The RA and Dec in J2000 were also recorded.

A master frame was selected to define the baseline of positions. Since we only need relative astrometry, the selection of the master frame is arbitrary and our final result is not sensitive to it. In practice, the exposure with a high signal-to-noise ratio (SNR) is preferred to include more reference sources.

The sources around SDSS J233635.75-010733.7 with distances between 20″ and 180″ were identified as reference sources. In total, there are 18 reference sources. However, some of them may be not available in some exposures with low SNRs. The centroid of the target quasar in the master frame is noted as X_0 and Y_0, and the centroids of the reference sources in the master frame are X_i and Y_i, where i = 1 - 18.

The centroids of the detected reference sources are adopted to determine the coordinate transformation between every frame and the master frame. A linear transformation is sufficient for small angular scales, i.e.,

\[
X_i' = a_i + b_i X_i + c_i Y_i, \quad (1)
\]

\[
Y_i' = d_i + e_i X_i + f_i Y_i, \quad (2)
\]

where X_i' and Y_i' are the centroids of the ith reference source in ith frame (excluding the master frame). If the detected reference sources are more than six in one frame, we can fit Eq. (1) and (2) to determine the transformation coefficients a_i \cdot \cdot \cdot f_i of this frame. The frames without sufficient reference sources were discarded. Figure 2 shows an example of the linear fitting.

The residual of the position of reference sources after the transformation determines the astrometric accuracy, i.e.,

\[
x_{ij} = X_i - (a_i + b_i X_i + c_i Y_i), \quad (3)
\]

\[
y_{ij} = Y_i - (d_i + e_i X_i + f_i Y_i), \quad (4)
\]

We then calculated the residual of the position of the target quasar in ith frame using the same transformation, i.e.,

\[
x_i = X_0 - (a_i + b_i X_0 + c_i Y_0), \quad (5)
\]

\[
y_i = Y_0 - (d_i + e_i X_0 + f_i Y_0), \quad (6)
\]

where X_0 and Y_0 are the centroids of the target quasar in ith frame (exclude the master frame).

We removed the outliers in x_{ij}, y_{ij}, x_i, and y_i that deviated from the mean value larger than 4σ. This process was performed iteratively until no new outlier is found. Then the systematic offset in x_i and y_i was corrected, i.e., the means of x_i and y_i were set to be zero.

The distribution of x_{ij}, y_{ij}, x_i, and y_i should be similar if the target quasar is a single AGN. However, the distribution of the residual of a binary AGN should be elongated along the direction of the two nuclei (see the simulations in Paper I). A large astrometric error or a small sample could hide the elongated distribution. Since the direction of the two nuclei is not known a priori, we performed the principle component analysis on x_i and y_i to find the direction of the maximum dispersion.

Then x_i, y_i, x_i, and y_i were projected to the direction of the maximum dispersion and the perpendicular direction. The corresponding distributions are noted as \(\bar{x} \), \(\bar{y} \), \(\bar{\bar{x}} \), and \(\bar{\bar{y}} \). The Kolmogorov-Smirnov (K-S) test is utilized to examine whether there is significant difference between these distributions. The distribution \(\bar{x} \) is expected to be different from the others. We performed K-S tests on three pairs, i.e., \(\bar{x} \) vs. \(\bar{\bar{x}} \), \(\bar{x} \) vs. \(\bar{\bar{y}} \), and \(\bar{\bar{x}} \) vs. \(\bar{\bar{y}} \) and the p-values are 0.0075, 0.77, and 0.076, respectively. Thus the distribution of the residual of the quasar position is indeed different from that of the reference sources in one direction. Furthermore, the standard deviations of \(\bar{x} \), \(\bar{\bar{x}} \), and \(\bar{\bar{y}} \) are 0.125, 0.099, 0.085, and 0.089 pixels, respectively, which are consistent with the result of K-S tests.

Figure 3 shows the distribution of \(\bar{x} \), \(\bar{\bar{x}} \), \(\bar{\bar{x}} \), and \(\bar{\bar{y}} \) and the direction of \(\bar{x} \). We performed 5000 bootstrap runs from \(\bar{x} \) and \(\bar{\bar{y}} \) to estimate the error of the direction of \(\bar{x} \). The angle between the x-axis and \(\bar{x} \) is noted as \(\theta \). Figure 4 shows the distribution of sin \(\theta \). The mean of sin \(\theta \) is 0.20 and the standard deviation is 0.20. The actual direction of the two nuclei is sin \(\theta = 0.03\); thus, the direction of \(\bar{x} \) is consistent with it at 1σ level.
Fig. 1. Images of SDSS J233635.75-010733.7 in SDSS g band (left), SDSS r band (middle), and PTF R band (right). The two nuclei are well resolved in the SDSS images (quasar A is a normal quasar and quasar B is a BAL quasar), but they are blended in the PTF image due to the relatively poor seeing and large pixel scale.

Fig. 2. An example of the linear fitting to determine the transformation coefficient between the master frame and a given frame. The residuals of $x$ and $y$ are well scattered around zero under the linear transformation; therefore, no higher order term is included in the current work.

Fig. 3. Distributions of the residual of the position in PTF R band. Squares are the residual of the quasar ($x^q$ and $y^q$); pluses are the residual of the reference sources ($x^r$ and $y^r$). The solid line indicates the direction of $\tilde{x}^q$.

Fig. 4. Distribution of the direction of $\tilde{x}^q$ from 5000 bootstrap runs (see the text in Sect. 3 for details).
4. Centroid Shift between $R$ and $g$ band

The method presented in Sect. 3 is appropriate for AGNs with strong variability, i.e., type I AGNs or blazars. In this section, we will employ the exposures of $R$ and $g$ band at the same time to alleviate this requirement. According to the optical spectra and SEDs of the two quasars in SDSS J233635.75-010733.7 (Figure 2 in Gregg et al. 2002), the fluxes of the two quasars are comparable in $R$ band, but the flux of the BAL quasar in $g$ band is lower than that of the blue quasar by a factor of 5 due to its intrinsic absorption. Thus, the distribution of the centroids in the two bands should be different. There are only $R$ and $g$ filters in PTF, though the filters with a larger spectral separation could promote the significance.

![Fig. 5. Comparison between the distribution of the residual of the position in PTF $R$ (red squares) and $g$ (green squares) band. The offset relative to the origin (defined by the mean of the residual of the reference sources) is not corrected, since it will not influence the relative positions of the residuals of the two bands.](image)

The same procedures in Sect. 3 were performed on $g$ band using the same reference sources identified in the master frame of the $R$ band. Figure 5 compares the distributions of the residuals in $R$ and $g$ band. Since the direction of the two nuclei is nearly parallel to the x direction, the residuals in $g$ and $R$ band are expected to be only different in the x direction. The significance indicated by K-S test between the residual in $g$ and $R$ band is $1.6 \times 10^{-59}$ in the x direction; while the significance is only 0.42 for the y direction. This result is consistent with the visual inspection.

5. Discussion and Conclusions

Using a confirmed binary AGN, we have tested the validity of the two centroid methods. Both of the two methods have revealed the signal of two nuclei. The significance of the method using one filter is relatively low (p-value=0.0075), since the variation of the BAL nucleus is not as strong as the type I nucleus. For the method using two filters, the distributions of the residual in $R$ and $g$ band are significantly different (p-value=$1.6 \times 10^{-69}$) and consistent with the expectation from the SEDs of the two quasars. Actually, if we randomly select 20 exposures of $R$ and $g$ band respectively, the significance of the difference between the distributions of $R$ and $g$ band is still at $10^{-69} - 10^{-6}$ level. These results indicate the success of the centroid method in uncovering the known binary AGN and its potential power in discovering new binary AGNs.

During the merging process of galaxies, the enhanced inflow may induce strong star formation and significant obscuration. Thus, even if two bands should be different, there are only $R$ and $g$ filters in PTF, though the filters with a larger spectral separation could promote the significance.

A binary system such as SDSS J233635.75-010733.7 is hard to discover by optical spectroscopy due to its high redshift ($z = 1.285$). The normally employed lines, e.g., [O III] and H$\beta$ lines, are already shifted into the infrared band. A large scale and deep infrared spectroscopy survey on AGNs is still not available at present. However, the centroid methods proposed here are not limited by the redshift in this content if the astrometric error is small enough to identify the centroid shift.

The multi-filter method does not require strong variations. Thus, even the exposures in the same night are helpful for identifying the relative shift between different bands. A large sample of binary AGNs should be quickly established by large-scale surveys, e.g., the Panoramic Survey Telescope and Rapid Response System and the Large Synoptic Survey Telescope.

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References

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Comerford, J. M., & Greene, J. E. 2014, ApJ, 789, 112
Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, ApJ, 676, 33
Foreman, G., Volonteri, M., & Dotti, M. 2009, ApJ, 693, 1554
Fu, H., Zhang, Z.-Y., Assef, R. J., et al. 2011, ApJ, 740, L44
Fu, H., Yan, L., Myers, A. D., et al. 2012, ApJ, 745, 67
Gregg, M. D., Becker, R. H., White, R. L., et al. 2002, ApJ, 573, L85
Hennawi, J. F., Strauss, M. A., Oguri, M., et al. 2006, AJ, 131, 1
Hernquist, L. 1989, Nature, 340, 687
Hopkins, P. F., Hernquist, L., Cox, T. J., & Kereš, D. 2008, ApJS, 175, 356
Junkkarinen, V., Shields, G. A., Beaver, E. A., et al. 2001, ApJ, 549, L155
Kauffmann, G., & Haehnelt, M. 2000, MNras, 311, 576
Komossa, S., Burwitz, V., Hasinger, G., et al. 2003, ApJ, 582, L15
Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 51
Koss, M., Mushotzky, R., Treister, E., et al. 2011, ApJ, 735, L42
Law, N. M., Kulkarni, S. R., Dokane, R. G., et al. 2009, PASP, 121, 1395
Liu, X., Greene, J. E., Shen, Y., & Strauss, M. A. 2010, ApJ, 715, L30
Liu, X., Civano, F., Shen, Y., et al. 2013, ApJ, 762, 110
Liu, Y. 2015, A&A, 580, A133
Maiolino, R., Comerford, J. M., Nevin, R., et al. 2015, ApJ, 813, 103
Pier, J. R., Munn, J. A., Hindsville, R. B., et al. 2003, AJ, 125, 1559
Sanders, D. B., Soifer, B. T., Elias, J. H., et al. 1988, ApJ, 325, 74
Shen, Y., Liu, X., Greene, J. E., & Strauss, M. A. 2011, ApJ, 735, 48
Smith, K. L., Shields, G. A., Bonning, E. W., et al. 2010, ApJ, 716, 866
Steinborn, L. K., Dolag, K., Comerford, J. M., et al. 2015, arXiv:1510.08465
Treister, E., Natarajan, P., Sanders, D. B., et al. 2010, Science, 328, 600
Van Wassenhove, S., Volonteri, M., Mayer, L., et al. 2012, ApJ, 748, L7
Volonteri, M., Haardt, F., & Madau, P. 2003, ApJ, 582, 559
Wang, J.-M., Chen, Y.-M., Hu, C., et al. 2009, ApJ, 705, L76
Yu, Q., Lu, Y., Mohayaee, R., & Collin, J. 2011, ApJ, 738, 92