

Searching for a Postprint on kpc-scale Low-redshift Dual Active Galactic Nuclei

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Abstract

The study of dual active galactic nuclei (AGNs) is crucial for understanding the formation, growth, and evolution of galaxies and supermassive black holes. However, the number of currently identified dual AGNs remains small, which limits predictions regarding galaxy mergers and the growth of dual supermassive black holes, as well as the detection of low-frequency gravitational waves. Based on the Million Quasars catalog, 187 new dual AGNs, 4 triple AGNs, and 1 quadruple AGN have been identified. The redshifts of these multiple systems are all less than 0.5, with the projected physical distance (r_p) between members in each system not exceeding 100 kpc, and the line-of-sight velocity difference (Δv) being less than 600 km/s. This sample supplements existing low-redshift dual AGN samples and contributes to the study of AGN formation and the evolutionary mechanisms of dual supermassive black holes. Visual inspection of the optical and infrared images of the aforementioned sample shows that approximately 24% of the dual AGNs exhibit distinct tidal features. Statistical analysis of redshift, projected distance, and line-of-sight velocity difference indicates that the number of dual AGNs tends to increase with decreasing redshift, while the line-of-sight velocity differences are primarily distributed around $\Delta v < 400$ km/s. The number of tidal samples is smaller at larger projected distances, with only 1 case in the (60–65) h_{70}^{-1} kpc interval, where the dimensionless Hubble constant is $h_{70} = H_0/70 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$. As the projected distance decreases, the number of tidal samples shows an increasing trend, reaching a peak (10 cases) in the (10–15) h_{70}^{-1} kpc interval, before gradually decreasing.

Full Text

Preamble

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Search for Low-Redshift Dual Active Galactic Nuclei at Kiloparsec Scales*

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摘要

The study of dual active galactic nuclei (DAGN) is crucial for understanding the formation, growth, and evolution of galaxies and supermassive black holes. However, the number of currently confirmed

dual active galactic nuclei remains small, which limits our ability to predict galaxy mergers and the growth of dual supermassive black holes, as well as the detection of low-frequency gravitational waves. Based on the Million Quasars (Milliquas) catalog, we have identified 187 new dual active galactic nuclei, 4 triple active galactic nuclei, and 1 quadruple active galactic nucleus. All of these multiple systems are located at redshifts $z < 0.5$, with projected physical separations (r_p) between members not exceeding 100 kpc and line-of-sight velocity differences (Δv) of less than 600 km/s. This sample supplements existing low-redshift DAGN catalogs and contributes to the study of AGN formation and the evolutionary mechanisms of dual supermassive black holes. Visual inspection of optical and infrared images of the sample reveals that approximately 24% of the dual active galactic nuclei exhibit distinct tidal features. Statistical analysis of redshift, projected distance, and velocity difference indicates that the number of dual active galactic nuclei tends to increase as redshift decreases, while the velocity differences are primarily distributed within $\Delta v < 400$ km/s. The number of samples with tidal features is lower at larger projected distances, with only one case identified in the $(60 - 65)h_{70}^{-1}$ kpc interval, where the dimensionless Hubble constant is defined as $h_{70} = H_0/70 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$. As the projected distance decreases, the number of tidal samples shows an increasing trend, reaching a peak of 10 cases in the $(10 - 15)h_{70}^{-1}$ kpc interval before gradually decreasing.

关键词

Galaxies: active, Galaxies: interactions, Galaxies: nuclei, Galaxies: general
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引言

Galaxy interactions and mergers have long been recognized as primary processes shaping the structure and morphology of galaxies [?, ?, ?, ?, ?]. These processes typically result in the emergence of structures such as dual or even multiple galactic nuclei, irregular morphologies, gas bridges or rings, and tidal tails. Interactions cause the gas within galaxies to lose angular momentum and migrate toward the galactic center [?, ?, ?]. This inward migration often triggers the accretion of Supermassive Black Holes (SMBHs), leading to the formation of Active Galactic Nuclei (AGNs). If the gas collapses under self-gravity and is transported to the vicinity of the central SMBH, it can fuel AGN activity; conversely, if the gas fails to reach the SMBH, it may trigger starburst activity [?]. Consequently, investigating AGNs induced by galaxy mergers is of great significance for studying star formation activity, SMBH growth, and the formation and evolution of galaxies [?, ?, ?, ?].

Within the theoretical framework of hierarchical galaxy evolution, the appearance of dual SMBHs is an inevitable consequence of galaxy mergers [?, ?, ?]. During the merger process, both SMBHs may undergo simultaneous accretion, resulting in the triggering of dual AGNs (defined as members with a separation of less than 100 kpc) [?, ?, ?]. However, accurately predicting the specific timing of dual AGN triggering remains a significant challenge [?, ?, ?, ?, ?, ?].

The incidence rate of dual AGNs can provide constraints for models involving galaxy merger rates and tidally triggered AGN activity [?]. Furthermore, the properties of their host galaxies can reveal the internal and external conditions required to activate dual AGNs simultaneously. During the galaxy merger process, dual AGNs form bound binary AGNs through dynamical friction [?], ultimately leading to the coalescence of the SMBH pair [?].

In the late stages of a merger, low-frequency gravitational waves are expected to be generated, the detection of which will...

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$h_{70} = H_0 / 70 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$.

Directly testing general relativity and revealing the statistical properties of supermassive black holes (SMBHs) in the early universe [?]. In recent years, studies primarily utilizing optical spectroscopy have searched for and identified dual active galactic nuclei (AGN) using the Sloan Digital Sky Survey (SDSS) [?, ?], significantly expanding the available dual AGN samples. Furthermore, dozens of dual AGN have been discovered by combining optical spectroscopy with high-resolution imaging across various wavebands [?], as well as through X-ray observations [?, ?]. Some studies have also employed the “double-peak” method [?] to identify dual AGN and high-confidence candidates. However, the double-

peak method suffers from a high false-positive rate in dual AGN identification, leading to low confirmation efficiency. For instance, physical processes such as accretion asymmetry in isolated AGN [?] or jet precession [?] can also produce double-peaked emission line structures.

Regarding the search for low-redshift dual AGN, one of the most representative works is by Liu et al. [?] in 2011. By searching for AGN with specific emission line characteristics in SDSS DR7 and visually inspecting their optical images, they released a sample containing 1,286 dual AGN and candidates. Approximately 30% of this sample exhibited clear tidal features of interaction, such as gas bridges, tidal tails, and gas rings. Prior to this, the sample size of kiloparsec-scale (kpc-scale) dual AGN remained small [?, ?, ?, ?] and lacked systematic statistical analysis. Recently, Pfeifle et al. (2024) released “The Big Multi-AGN Catalog DR1” [?], which compiles 156 confirmed dual AGN and 4,180 candidates documented in the literature between 1970 and 2020. It is evident that the sample of confirmed dual AGN is still relatively scarce. Currently, the latest version (v8.0) of the Million Quasar Catalog (MQC) contains 1,021,800 quasars and candidates, including 103,216 AGN and candidates with redshifts below 0.5 [?], providing a rich dataset for the study of low-redshift dual AGN.

Based on the latest MQC, this paper conducts a systematic search for multi-AGN systems within the redshift range $z < 0.5$, aiming to identify new low-redshift multiple AGN systems. By investigating the statistical properties of dual AGN, we seek to understand the galaxy merger process and its impact on galaxy evolution. Section 2 introduces the data and source selection methods; Section 3 provides a preliminary statistical and tidal feature analysis of the sample; and Section 4 discusses and summarizes the research results. Throughout this paper, we adopt the Λ CDM (Λ -Cold Dark Matter) cosmological model with the following parameters:

Matter density parameter $\Omega_m = 0.3$, dark energy density parameter $\Omega_\Lambda =$

0.7 以及哈勃常数 $H_0 = 70 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$, 其中

The unit for projected physical distance (r_p) is $h^{-1}\text{Mpc}$.

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Data and Source Selection

The initial sample for this study is the Million Quasars Catalog (MQC) version 8.0, which contains 907,144 Type I quasars and active galactic nuclei (AGN), as well as 66,026 quasar candidates identified through radio/X-ray associations (including double radio lobe structures) with a 99% confidence level. If blazars and Type II objects are included, the total number of AGN reaches 1,021,800 [?]. Compared to previous statistical studies of dual AGN [?, ?, ?], the initial sample size in this work has increased by several orders of magnitude. In the MQC catalog, objects classified as Q (Quasi-Stellar Object, QSO, broad-line

nucleus dominated), A (AGN, broad-line Seyfert type/host galaxy dominated AGN), K (narrow-line QSO), and N (narrow-line Seyfert-type AGN) all have spectroscopic redshifts. For Class B (BL Lac type) objects, redshift information is not mandatory; therefore, their redshifts may be missing or provided as photometric redshifts, typically accurate to 0.1. All sources in our sample possess redshifts, and all are spectroscopic redshifts [?].

Optical imaging data are derived from the Dark Energy Spectroscopic Instrument Legacy Survey (DESI-LS). This survey project has constructed a deep all-sky map through optical and infrared imaging observations. Its data are highly suitable for the morphological analysis of galaxies in the optical bands, offering significant advantages in identifying typical structural features in merging galaxy systems, such as tidal tails and gas bridges. Compared to the Sloan Digital Sky Survey (SDSS) and the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), DESI-LS has significant advantages in detection depth (with a limiting magnitude of 24.5 in the r -band) and sky coverage (33,000 deg²), providing a more complete photometric foundation for the identification of galaxies, stars, and AGN [?].

Infrared image data are sourced from the Two Micron All Sky Survey (2MASS), a systematic project that mapped the entire sky in three infrared bands (J , H , and K_s) using two ground-based telescopes. In the infrared regime, $J - K_s$ color maps (where J and K_s represent the magnitudes in the J and K_s bands, respectively) are particularly useful for identifying and studying galaxy interactions and tidal features, as they can reveal details that

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might be difficult to observe in the optical bands. To obtain these color maps, we followed these steps: (1) Data acquisition: We downloaded images for each pair in the sample in both the J and K_s bands, ensuring consistent image dimensions. The pixel size for each image is approximately $1'' \times 1''$. (2) Color map calculation: We calculated the $J - K_s$ magnitude difference for each pixel to obtain the infrared $J - K_s$ color map for the source.

We selected 103,216 AGN with redshifts below 0.5 as the input sample. Then, based on their redshifts and the projected distance threshold set by criterion (2), we calculated the angular distance corresponding to $100h_{70}^{-1}$ kpc at these redshifts. Subsequently, we performed a self-match of the input sample using the catalog cross-matching tool TOPCAT [?], with a matching radius equal to the maximum value of the aforementioned angular distances. After obtaining the self-matching results, we applied criterion (2) to filter the samples that met the conditions. Using the formula proposed by Hogg and the redshifts of these samples, we calculated the radial velocity difference Δv between each pair of AGN [?].

Finally, 319 dual AGN samples were extracted using criterion (3). Among

these samples, some confirmed dual AGN systems already exist. Therefore, we cross-matched our sample with several currently large and comprehensive dual AGN catalogs [?, ?, ?, ?, ?] and excluded the previously identified dual AGN. Furthermore, we performed a visual inspection of the samples using DESI-LS optical images and 2MASS infrared $J - K_s$ color maps, identifying 5 multiple systems and excluding 6 false dual systems. The final sample contains 192 systems (187 dual AGN, 4 triple systems, and 1 quadruple system). Relevant data for a portion of the sample are listed in Table 1 .

The selection of the dual AGN sample in this study follows three criteria: (1) all redshifts satisfy $z < 0.5$; (2) the projected distance between each source is $r_p < 100h_{70}^{-1}$ kpc; (3) the line-of-sight velocity difference is $\Delta v < 600$ km/s.

The latter two selection criteria were proposed by Liu et al. [?] and Silverman et al. in 2011 [?], and are similar to the selection conditions recently proposed by Pfeifle et al. [?]. Among them, the projected distance threshold of $100h_{70}^{-1}$ kpc is slightly higher than the standard used in typical galaxy pair studies [?, ?], but it is comparable to the lower limit of the velocity dispersion for galaxy pairs in the projected distance range of $150h_{70}^{-1}$ kpc $\leq r_p \leq 5000h_{70}^{-1}$ kpc.

First, we used criterion (1) to select from the MQC...

Obj. Name
RA (J2000d)
Dec (J2000d)
J0018–0045A
–0.75948
J0018–0045B
–0.74598
J0024+0815A
J0024+0815B
J0033–4436A
–44.61373
J0033–4436B
–44.61784
J0034–4318A
–43.31656
J0034–4318B
–43.31618

J0034-4330A
-43.51141
J0034-4330B
-43.51462
J0046+0007A
J0046+0007B
J0100+3112A
J0100+3112B
J0103+0029A
J0103+0029B
 $\Delta\theta / ''$
rp / h-1
 $\Delta v / (\text{km} \cdot \text{s}^{-1})$
r/mag
Class
Ftidal
Obj. Name
RA (J2000d)
Dec (J2000d)
J0107-1730A
-17.50697
J0107-1730B
-17.53864
J0113-1450A
-14.84566
J0113-1450B
-14.84919
J0114-5523A
-55.39700
J0114-5523B
-55.39705

J0120–0829A

–8.49063

J0120–0829B

–8.48844

J0120–4407A

–44.13282

J0120–4407B

–44.12858

 $\Delta\theta / ''$

rp / h–1

 $\Delta v / (\text{km} \cdot \text{s}^{-1})$

r/mag

Class

Ftidal

The classification results were consistent across 98% of the sample. For systems where classifications differed, a majority decision rule was applied (i.e., at least two members reaching a consensus). Ultimately, we identified 41 dual AGNs with clear tidal features through optical image identification. [Figure 1: see original paper] displays composite DESI-LS $grz(i)$ -band images of dual AGNs exhibiting these prominent tidal signatures.

Compared to visible light, infrared radiation possesses a stronger capability to penetrate dust, making it an essential tool for studying regions obscured by dust. When two galaxies undergo a merger, infrared imaging can sometimes reveal tidal features that might be overlooked in optical images. Signs of interaction are clearly visible in the $J - K_s$ color maps.

Among these, J0917+5416 does not exhibit obvious tidal features in optical imaging; however, its infrared $J - K_s$ color map reveals significant morphological distortion and a gas bridge connecting the two AGNs, which are clear indicators of interaction. Seven other systems exhibit similar characteristics, although visual inspection of most infrared $J - K_s$ color maps yielded less than ideal results. In those cases, only a blue connecting region between the two AGNs is observable, which may result from interaction-triggered active star formation forming a blue gas bridge or ring. However, due to limitations in imaging depth, most AGN cores were not detected in the imaging.

Consequently, the blue “bridge” between the two nuclei may be a projection effect (where the blue radiation from the two nuclei simply overlaps along the line of sight) rather than a true physical connection. While such features can

serve as supporting evidence for galaxy interactions, they require verification through deeper infrared imaging.

Dual AGNs with Tidal Features

To explore dual AGNs that have clearly undergone strong tidal interactions, we selected a sub-sample from our primary dataset to form the “Tidal Sample.” This selection was based on a visual inspection of DESI-LS images (using grz bands from DR9 or $grzi$ bands from DR10) and infrared $J - K_s$ color maps, primarily identifying sources with tidal features such as gas bridges, tails, shells, or rings.

The rationale for employing visual inspection is three-fold: (1) High sensitivity to Low Surface Brightness (LSB) features: Visual inspection is more sensitive to LSB features such as gas bridges, tails, shells, or rings. These features are often critical for identifying tidal interactions, yet automated detection methods struggle to recognize such subtle structures. (2) Lower false-positive rate: Compared to automated techniques like model fitting, visual inspection is less prone to false positives, effectively reducing the risk of misidentifying noise or other spurious, elusive features as genuine tidal interactions. (3) Avoidance of phase bias: Although the quantitative merger indices proposed by Conselice [?] and Lotz et al. [?, ?] are more objective and reproducible, such methods may have selective preferences for specific merger stages (such as the first pericentric passage or the final coalescence), which can introduce bias. Visual inspection offers greater flexibility and comprehensiveness in assessing tidal features throughout the entire merger process, helping to mitigate this bias [?]. To minimize uncertainties arising from subjectivity, three team members conducted three rounds of independent visual inspections for each system, remaining blinded to each other’s identification results during the process.

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The field of view (FOV) for each image is labeled in the bottom right corner. Additionally, the redshift (z_A, z_B), projected distance r_p , and angular separation $\Delta\theta$ (Sep) for each AGN pair are provided. [Figure 1: see original paper] DESI-LS $grz(i)$ -band images of sources in the dual AGN sample with clear tidal features. Red and blue circles indicate the locations of AGNs. North is up and east is to the left. The field of view (FOV) of each image is labeled at the bottom right corner. Additionally, the redshift (z_A, z_B), projected distance r_p , and angular separation $\Delta\theta$ (Sep) of each dual AGN are provided.

2 Examples of infrared $J - K_s$ color maps are shown for interacting sources of dual AGN systems. The positions of the AGNs are marked with black crosses. North is up and east is to the left.

$r_p < 100h_{70}^{-1}$ kpc. For example, in a triple system containing three AGNs (A, B, and C), the projected distances between A and B, and between B and C, might satisfy the selection criteria, while the distance between A and C does not.

Even in such cases, we still classify the system as a triple AGN system.

Ultimately, a total of 45 pairs (approximately 24%) of dual AGNs were confirmed to exhibit tidal features in optical images or infrared $J - K_s$ color maps. In comparison, Liu et al. [?] found through visual inspection of SDSS images that approximately 30% of their 1,286 pairs exhibited tidal features, which is slightly higher than the results of this study. We have labeled each pair as either “T” (possessing tidal features) or “N” (no tidal features), as shown in . It should be noted that the tidal sample may exclude sources in the early merger stages prior to the first pericentric passage, as such mergers typically lack observable tidal features [?]. Furthermore, the strength of tidal features is influenced by the properties of the host galaxies and the orbital parameters of the merger (for instance, major mergers rich in gas on prograde orbits may easily produce strong tidal features, while other types of mergers may lack them) [?, ?]. Specifically, merger types that may lack obvious tidal features include minor mergers with mass ratios exceeding approximately 30 [?], spherical mergers characterized by high bulge-to-disk ratios [?], and mergers occurring on highly retrograde orbits [?].

Sample Inhomogeneity

The MQC is a heterogeneous AGN catalog that aggregates results from several different surveys, leading to variations in target selection criteria, spectral quality, and data completeness, which may affect our statistical analysis. Due to the heterogeneity of the MQC sample, the multiple AGN sample in this study may be influenced by the varying depths of different survey data and different AGN selection methods (such as those based on spectroscopy, X-rays, or optical variability). Consequently, the statistical results of our multiple AGN systems may be subject to certain systematic biases, particularly regarding low-luminosity AGNs.

In the MQC, each object is labeled with a corresponding classification code reflecting its physical properties and multi-wavelength detection status. The basic classifications include Q, A, B, K, and N. Additionally, suffix letters R (radio), X (X-ray), and 2 (dual radio lobes) indicate that the object has observations in the corresponding bands. To unify the classification and simplify the statistical analysis, this paper adopts the following categorization strategy: (1) Objects labeled with “Q” (e.g., Q, QR, QRX, QX) are unified into the QSO (Quasar) category; (2) Objects labeled with “A” (e.g., A, AR, AX, ARX, AR2, AR2X) are unified into the AGN category (broad-line Seyfert-type AGN); (3) Broad-line radio-bright sources labeled “BR” or “BRX” are unified as radio-loud AGN / Flat-Spectrum Radio Quasars (FSRQ) and are not classified as BL Lac objects.

Sample Analysis and Discussion

Through self-matching of the MQC combined with systematic searching and analysis, this study identified 192 new multiple AGN systems within the low-redshift range ($z < 0.5$). These include 187 dual AGNs, 4 triple AGNs, and 1 quadruple AGN. The projected distances of these systems all satisfy $r_p < 100h_{70}^{-1}$ kpc, and their radial velocity differences satisfy $\Delta v < 600$ km/s. It should be

noted that for systems with three or more components, the projected distances between all possible pairs do not necessarily satisfy the criteria.

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- (4) Objects labeled “B” or “B2” are classified as BL Lac objects (specifically referring to typical BL Lac objects in the MQC); (5) Objects labeled “K” or “KX” are classified as Narrow-Line Quasars (NLQSO), while those labeled “N”, “NR”, “NRX”, “NX”, or “NR2” are classified as NLAGN (narrow-line Seyfert-type/host-galaxy-dominated AGN). It should be clarified that composite labels in the MQC (such as ARX, QRX, etc.) are primarily used to indicate multi-wavelength observational information (radio, X-ray, dual radio lobes, etc.) and do not alter the fundamental physical classification of the object [?]. Therefore, unless otherwise specified, all objects in this study are categorized and analyzed according to their primary classifications (QSO, AGN, NLAGN, BL Lac).

The redshift distribution results indicate that NLAGN and AGN types dominate the sample, accounting for 55.1% and 34.8% of the total, respectively. In contrast, the numbers of QSOs, BL Lacs, and radio-loud AGNs/FSRQs are relatively small, collectively accounting for only about 10%. This distribution characteristic suggests that in the low-redshift dual AGN systems of the MQC, the majority are low-luminosity galaxies such as narrow-line AGNs and Seyfert-type broad-line AGNs, while QSOs, FSRQs, and BL Lacs are relatively rare.

Statistics and Analysis of Dual AGNs

Our sample consists of 390 AGNs from 192 multiple AGN systems. provides a detailed statistical breakdown of the different type combinations within the dual AGN sample. The statistical results show that the AGN/NLAGN combination (35.3%) and the NLAGN/NLAGN combination (34.8%) dominate the sample, indicating that narrow-line AGNs constitute a large proportion of low-redshift dual AGN systems. This trend is generally consistent with the findings of Liu et al., where narrow-line AGNs accounted for up to 96% of the sample [?].

Furthermore, the AGN/AGN combination, composed of broad-line Seyfert-type AGNs, also accounts for a certain proportion (15.0%). In contrast, quasar combinations (e.g., QSO/QSO at 2.1%, AGN/QSO at 3.2%, and NLAGN/QSO at 1.6%) are relatively rare, which may reflect the scarcity of low-redshift dual quasars. Additionally, combinations involving BL Lac and

NLQSO types are very rare, with each combination accounting for only 1%-3% of the sample. It should be noted that the distribution characteristics of AGN type combinations in the sample may be limited to some extent by the inhomogeneity and selection effects of the MQC parent sample itself.

Total: 374 AGN: 130 radio-loud AGN / FSRQ: 3 NLQSO: 17

Count

NLAGN: 206 QSO: 17 BL Lac: 1

Redshift

3 Redshift distribution for different classes of sources in the dual AGN sample

The distribution of redshifts for the dual AGN sample is shown in [FIGURE:N]. The figure illustrates that the number of dual AGN gradually increases as redshift decreases. Specifically, the tidal sample is primarily concentrated within the range of $z < 0.14$, with a peak occurring between $0.06 < z < 0.14$. The redshift distribution of these dual AGN exhibits a clear concentration in the low-redshift region, a trend that may be attributed to selection effects inherent in the parent Million Quasars Catalog (MQC). Consequently, this potential systematic bias must be taken into account when interpreting these results.

Further analysis reveals that 48 dual AGN in our sample are located at redshifts greater than 0.16, accounting for approximately 26% of the total sample. In contrast, this proportion is only 1.9% in the sample provided by Liu et al. [?], indicating that our sample offers enhanced coverage at higher redshifts. However, it is important to note that, as discussed in the previous section regarding the non-uniformity of the MQC catalog, the inclusion of a significant number of dual AGN at higher redshifts compared to prior studies does not imply that our sample is statistically complete.

Combination

Count

Combination

Count

Combination

Count

AGN / AGN

15.0%

AGN / NLAGN

35.3%

NLQSO / AGN

BL Lac / BL Lac

AGN / QSO

NLQSO / NLAGN

NLQSO / NLQSO

BL Lac / NLAGN

NLAGN / QSO

NLAGN / NLAGN

34.8%

QSO / QSO

Optical pair Infrared pair

$r_p/h-1$ 70 kpc

redshift

[Figure 4: see original paper] presents the projected distance (r_p) versus redshift for our dual AGN sample. Black dots represent the entire population of dual AGNs. Blue and red open circles denote dual AGNs that exhibit distinct morphological tidal features identified in optical images and infrared $J - K_s$ color maps, respectively.

The distribution of these sources is further illustrated by the histograms: dotted histograms represent the distribution of all dual AGNs, while solid histograms show the distribution of the tidal sample. Additionally, the green, red, and dark blue dotted curves correspond to constant angular separations of $1''$, $10''$, and $100''$, respectively.

Angular separation/''

After passing the pericenter, the systems gradually move apart, and the previously generated tidal features begin to dissipate. Furthermore, there are cases with small projected distances; for instance, in our dual AGN sample, three systems exhibit a separation of $r_p < 5h_{70}^{-1}$ kpc between members.

Among these, the redshift information for J1659+6437 and J1053+4710 is sourced from the SDSS, while the two sources in J1746+6836 are obtained from the Swift Burst Alert Telescope AGN Spectroscopic Survey (BASS DR2). The angular separations between the members of these three systems are $3.23''$, $1.96''$, and $3.26''$, respectively. As shown in [Figure 5: see original paper], within the redshift range $0 < z <$

0.5 范围内, $r_p = 5 h-1$

The angular separation corresponding to a physical distance of 70 kpc decreases as redshift increases. At $z \approx 0.09$, this angular separation is approximately $3''$, which is comparable to the fiber diameter of the Sloan Digital Sky Survey (SDSS). Consequently, both J1659+6437 and J1053+4710 can be resolved by SDSS fibers. Furthermore, since the Beijing-Arizona Sky Survey (BASS) utilizes slit spectroscopy, J1746+6836 can also be resolved, provided that the atmospheric seeing conditions are favorable.

When the system is at a higher redshift, if the projected separation is $r_p = 5h_{70}^{-1}$ kpc, the angular distance between the members will be smaller than the fiber diameters used in current mainstream spectroscopic surveys. This prevents

the fibers from resolving the system into two independent sources. For example, at $z > 0.09$, the angular separation of a dual AGN system with a scale of $r_p = 5h_{70}^{-1}$ kpc will be less than $3''$, making it unresolvable for SDSS fibers. Such resolution limits hinder the systematic identification of close dual-core systems and lead to the omission of close systems at higher redshifts. In these cases, identification must rely on slit spectroscopy.

Total pair Tidal pair

Within the projected distance range of $0 \leq r_p \leq 100 h_{70}^{-1}$ kpc, the overall sample of dual AGNs exhibits a trend of slightly increasing frequency as the projected distance decreases. However, there are sparse distributions in certain intervals, such as $40 h_{70}^{-1}$ kpc $\leq r_p \leq 50 h_{70}^{-1}$ kpc, which may be attributed to the inherent non-uniformity of the overall sample. Additionally, the limited number of samples in the $0 \leq r_p \leq 15 h_{70}^{-1}$ kpc range is likely due to the angular resolution constraints of the survey.

In contrast, the tidal feature sample is distributed only within the range of $0 \leq r_p \leq 65 h_{70}^{-1}$ kpc and becomes increasingly scarce at larger projected distances, with only one case identified in the $(60 - 65) h_{70}^{-1}$ kpc interval. As the projected distance decreases, the number of tidal samples shows a significant upward trend, reaching a peak of 10 cases within the $10 h_{70}^{-1}$ kpc $\leq r_p \leq 15 h_{70}^{-1}$ kpc interval.

This trend suggests that larger physical separation distances between galaxies may be unfavorable for the formation or maintenance of tidal disturbances. First, dual AGNs at larger separations may still be in the early stages of merging, during which significant tidal disturbances have not yet been generated. Second, these systems may have already experienced a close encounter but failed to form observable tidal structures due to specific orbital or mass configurations. Furthermore, it is possible that these galaxies...

5 kpc SDSS fiber ($3''$)

z 0.09

Redshift

Corresponding angular separation distribution. The gray dashed line represents the SDSS fiber diameter of $3''$, which corresponds to a projected distance of 70 kpc. 5 Angular separation as a function of redshift corresponding to a projected distance of $5 h^{-1}$ kpc. The gray dashed line indicates the SDSS fiber diameter of $3''$.

When $\Delta v > 400$ km/s, the number of sources in both the total sample and the tidal sample is small (15 dual AGN cases, of which only 3 are in the tidal sample). Although there is a trend for the total sample size to increase with Δv , this is not statistically significant due to the small absolute numbers. When $\Delta v <$

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400 km/s, the number of sources in both the total and tidal samples increases as Δv decreases. However, contrary to the trend shown in [Figure 4: see original paper], the increase in the overall sample is more significant than that in the tidal sample. This may be caused by the influence of the galaxies' peculiar velocities on the measured line-of-sight velocities.

On the other hand, this may also be influenced by sample selection effects: dual AGNs with larger velocity differences are more likely to be in the early stages of merging, where distinct tidal features have not yet formed; alternatively, they may have experienced a close encounter, but the resulting tidal perturbations have already faded and are difficult to observe. Furthermore, systematic biases in the measurement of line-of-sight velocity differences cannot be ruled out. For instance, observational constraints (such as the sensitivity of spectroscopic data) may lead to an underestimation of dual AGNs with high velocity differences.

From the figure, it can be seen that most dual AGNs are distributed within $100''$, particularly those systems with tidal features. We identified a total of 42 dual AGNs with clear tidal features, 41 of which satisfy the angular separation condition $\Delta\theta < 100''$. In the larger angular separation range ($\Delta\theta > 100''$), only one system, J1332+6246, exhibits obvious tidal features in optical imaging. Additionally, in the dual AGN sample with angular separations less than $10''$, the tidal sample accounts for approximately 59%. This may indicate that tidal features are more likely to appear within smaller angular separation ranges; as the angular separation increases, the visibility or formation conditions of tidal interactions are affected.

DESI-LS *grz* (*i*)-band images. Multiple AGN systems are typically located in the peak regions of the cosmic density distribution [?], making them more suitable than single quasars for identifying protoclusters [?] and providing important clues for studying the origin of galaxy clusters [?]. Simultaneously, the existence of multiple AGNs further supports the hierarchical merging theory of cosmic structure, wherein high-density environments provide sufficient cold gas for multiple supermassive black holes (SMBHs) to maintain simultaneous AGN activity [?]. Furthermore, the interactions between multiple black holes in such systems may directly lead to the formation of SMBHs [?]. Therefore, multiple AGN systems serve as ideal laboratories for understanding the co-evolution of SMBHs and their host galaxies [?].

Whole sample Tidal sample

$$\Delta v / (\text{km} \cdot \text{s}^{-1})$$

The distribution of AGNs, while the grey dashed line represents the distribution of the tidal sample. [Figure 6: see original paper] Distribution of LOS velocity difference Δv for dual AGNs. The black solid curve represents the distribution of

Multiple AGNs

all dual AGNs, while the gray dashed curve shows the tidal

sample distribution.

7 DESI-LS grz (i)-band images of the five multiple AGNs in this sample, including four triplets and one quadruplet. Red circles indicate the locations of AGNs. North is up, and east is to the left.

The Proportion of Dual and Multiple AGNs

The current proportion is approximately 0.04%, while the occurrence rate of triple and quadruple AGNs is about 0.0016%. In contrast, Liu et al. utilized a parent sample of 138,070 AGNs within a redshift range of $0.02 < z < 0.33$ and identified 1,286 new multiple AGN systems. This collection includes 1,244 dual AGNs, 39 triple AGNs, 2 quadruple AGNs, and 1 quintuple AGN.

In this study, through a systematic search of 1,021,800 AGNs in the Million Quasars Catalog (MQC), we identified 192 new multiple AGN systems within the low-redshift range ($z < 0.5$). This group consists of 187 dual AGNs, 4 triple AGNs, and 1 quadruple AGN. Within the MQC, the occurrence of dual AGNs is as follows:

AGN. In their sample, the occurrence rate of dual AGNs is approximately 1.8%, while the proportion of multiple AGN systems (with ≥ 3 nuclei) is approximately 0.09% [?].

Our sample within the $0.02 < z < 0.33$ range includes 123 dual AGNs, 3 triple AGNs, and 1 quadruple AGN. If the systems from the sample by Liu et al. are included in the statistics, the number of dual AGNs within this redshift range increases to 189, while the numbers of triple and quadruple AGNs become 5 and 1, respectively. The corresponding occurrence rates of these samples within the MQC catalog are presented in Table 3 .

As shown in the table, the proportion of multiple AGNs in the sample by Liu et al. is significantly higher than the results derived from the MQC. This discrepancy may primarily stem from the inhomogeneity of the MQC and differences in sample composition. In the MQC sample for $z < 0.5$, the proportion of Narrow-Line AGNs/Quasars (NLAGN/NLQSO) is approximately 46%, whereas in the sample by Liu et al., this proportion is as high as approximately 94% [?].

Redshift

Sample

Dual AGN

Mutiple AGN

$0 < z < 0.5$

This work

0.04%

0.0016%

0.02%

0.0013%

0.04%

0.0019%

0.09%

This work (exclude Liu et al.[11])

$0.02 < z < 0.33$

This work (include Liu et al.)

$0.02 < z < 0.33$

Sample of Liu et al.

The proportion of dual and multiple AGNs within the MQC sample is significantly lower than the proportion reported by Liu et al. in their parent sample [?]. This discrepancy likely stems from the inhomogeneity of the MQC and differences in sample composition, particularly regarding the fraction of narrow-line AGNs (NLAGN/NLQSO). Specifically, NLAGNs account for approximately 46% of the MQC, whereas they comprise as much as 94% of the sample studied by Liu et al. [?].

Through visual inspection of DESI-LS optical images and 2MASS infrared $J - K_s$ color maps, we found that approximately 24% of the dual AGNs exhibit morphological tidal features. In comparison, Liu et al. found that about 30% of their 1,286 dual AGNs showed tidal signatures, which is slightly higher than our result [?]. Given that the imaging depth of DESI-LS is superior to that of SDSS, one would expect a higher detection rate of tidal features; however, the actual results are lower than anticipated. This may be attributed to selection effects within the MQC catalog, suggesting that the identified dual AGNs might be biased toward the early stages of the merging process, during which tidal disturbances are not yet prominent. Furthermore, we analyzed the statistical properties of these dual AGN samples. The statistical results indicate that BLAGN/NLAGN combinations (35.3%) and NLAGN/NLAGN combinations (34.8%) dominate the sample. This suggests that narrow-line AGNs account for a high proportion of low-redshift dual AGN systems, which is generally consistent with the findings of Liu et al., who reported that narrow-line AGNs comprise 96% of their sample [?]. The dual AGN samples are distributed within the range of (0 – 100)

总结

This study systematically selected a group of low-redshift ($z < 0.5$) dual and multiple AGN systems based on the Million Quasars (MQC) Catalog (Version

8, 2023). We adopted strict selection criteria, including: (1) a projected separation $r_p < 100 h_{70}^{-1}$ kpc; and (2) a line-of-sight velocity difference $\Delta v < 600$ km/s. The MQC catalog synthesizes optical, radio, and X-ray data for the identification of QSOs and AGNs. The screening of AGNs was based on the following standards: (1) spectroscopic identification, requiring at least two spectral lines, or one spectral line optimized in conjunction with existing photometric redshifts; (2) correlation with radio/X-ray data, where some QSO candidates were inferred from radio or X-ray data with a confidence level of 99%; (3) data quality control, which involved removing low-confidence objects and those flagged as stars in Gaia-EDR3; and (4) de-duplication to ensure each data entry corresponds to a unique object.

However, it should be noted that because the MQC catalog is a compilation of various observation methods and archival data, it represents a heterogeneous sample. Consequently, there may be systematic biases in the coverage across different observation regions or redshift intervals. Although the dual AGN sample in this paper possesses a high degree of authenticity, this heterogeneity may still influence the results. Ultimately, we identified 187 dual AGNs, 3 AGN triple systems, and 1 AGN quadruple system, significantly enriching the statistical sample of low-redshift dual AGNs and providing valuable data support for subsequent research. Within the range of $0.02 < z < 0.33$, this paper...

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A distinct peak is observed at $(10 - 15) h_{70}^{-1}$ kpc, while a valley appears near $(45 - 50) h_{70}^{-1}$ kpc. The tidal sample exhibits a prominent peak at $r_p \approx (10 - 15) h_{70}^{-1}$ kpc, reaching 10 pairs within the $(15 - 20) h_{70}^{-1}$ kpc range before rapidly declining; by $(60 - 65) h_{70}^{-1}$ kpc, only one pair remains, and it is completely absent beyond $65 h_{70}^{-1}$ kpc. This downward trend may be related to several factors. Some of these systems may still be in the stage prior to their first encounter, at which point significant tidal perturbations have not yet formed. Secondly, slow-moving galaxy interactions may have previously triggered morphological perturbations, but these features have since dissipated or are difficult to detect due to low surface brightness. Furthermore, some systems may not have produced significant morphological changes during previous close encounters, suggesting that these AGN activities might not be driven by galaxy mergers but are instead stochastic occurrences.

The redshift distribution of the dual AGNs shows a significant concentration in the number of sources at $z < 0.25$. Predictions by Chen et al. [?] based on cosmological simulations suggest that the fraction of dual AGNs should increase with redshift, peaking during the “Cosmic Noon” era. Therefore, the redshift concentration observed in our sample is likely primarily influenced by the selection effects of the MQC catalog. Regarding the line-of-sight velocity difference Δv , the number of dual AGNs shows a decreasing trend as Δv increases, with only a very small number of systems approaching 600 km/s. The majority of the sample is concentrated within the range where Δv is less than 300 km/s.

This trend indicates that larger line-of-sight velocity differences typically correspond to larger physical separations, which are unfavorable for the formation or maintenance of distinct tidal features.

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Search for Low-Redshift Dual Active Galactic Nuclei at Kiloparsec Scales

Abstract

Dual Active Galactic Nuclei (dual AGNs) are key products of the hierarchical growth of galaxies and the evolution of Supermassive Black Holes (SMBHs). They serve as critical observational evidence for the study of galaxy mergers and the co-evolution of galaxies and their central black holes. This paper focuses on the search for dual AGNs at the kiloparsec (kpc) scale in the low-redshift universe. By utilizing multi-wavelength observational data and high-resolution imaging techniques, we aim to identify and characterize these rare systems to better understand the physical processes governing black hole accretion and feedback during the late stages of galaxy mergers.

1. Introduction

In the framework of the Λ CDM cosmological model, galaxies grow through a series of merger events. When two galaxies, each harboring a central supermassive black hole, undergo a merger, the two SMBHs will eventually sink toward the center of the new potential well due to dynamical friction. During this process, if both SMBHs are simultaneously undergoing gas accretion and manifesting as AGNs, the system is defined as a dual AGN.

The study of dual AGNs is of profound significance for several reasons. First, they represent a specific stage in the evolution of binary SMBHs, bridging the gap between widely separated pairs and sub-parsec binary systems that eventually merge and emit gravitational waves. Second, the interaction between the two merging galaxies can trigger intense star formation and enhance black hole accretion, providing a laboratory to study the “co-evolution” of galaxies and SMBHs. Despite their theoretical importance, identifying dual AGNs at kpc scales remains a significant observational challenge due to the high spatial resolution required and the potential for confusion with single AGNs or projection effects.

2. Sample Selection and Identification Methods

To search for dual AGNs at kpc scales, we primarily rely on large-scale spectroscopic surveys and high-resolution imaging. The identification process typically involves several stages:

2.1 Candidate Selection via Spectroscopy The initial candidates are often selected from the Sloan Digital Sky Survey (SDSS) based on double-peaked narrow emission lines (e.g., [O III] λ 5007). Such features may indicate the distinct orbital motions of two independent narrow-line regions (NLRs) associated with two separate SMBHs. However, double-peaked lines can also be produced by single AGNs through gas

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ABSTRACT

Research on dual AGNs (Active Galactic Nuclei) is crucial for understanding the formation, growth, and evolution of galaxies and supermassive black holes (SMBHs). However, the current number of identified dual AGNs remains scarce,

which limits our understanding of galaxy mergers, the growth of SMBH pairs, and the prediction and detection of low-frequency gravitational waves. A total of 187 new dual AGNs, 4 triple AGN systems, and 1 quadruple AGN system were identified based on the Million Quasars Catalog. All of these multiple AGN systems have low redshifts ($z < 0.5$), with projected distance (r_p) between members less than 100 kpc and line-of-sight velocity differences (Δv) smaller than 600 km/s. This sample complements existing low-redshift dual AGN samples and provides valuable insights into AGN triggering mechanisms and the evolution of SMBH pairs. A visual inspection of the optical and infrared images of the identified samples reveals that approximately 24% of the dual AGN systems exhibit clear tidal features. Statistical analysis of their redshift, projected distance, and line-of-sight velocity difference indicates that the number of dual AGN increases with decreasing redshift, and that most Δv values are distributed below 400 km/s. The number of dual AGN systems with tidal features is relatively small in larger projected distances, with only one system found in $(60 - 65) h^{-1} 70$ kpc. As the projected separation decreases, the number of such systems increases, reaching a peak of 10 cases in $(10 - 15) h^{-1} 70$ kpc, and then gradually decreases in smaller scales.

Key words galaxies: active, galaxies: interactions, galaxies: nuclei, galaxies: general

Note: Figure translations are in progress. See original paper for figures.

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