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Dual and binary supermassive black holes

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We review recent results focused on dual and binary active galactic nuclei (AGN) obtained by our collaboration. Our research, conducted at both low and high redshifts, involves statistical analyses of known AGN pairs (less than 100 kpc of separation), identification of new samples of dual AGN at sub-kpc/kpc scale separation at z>0.5, and investigation of binary AGN candidates (sub-pc separation). Studying these systems over a wide range of frequencies and redshifts contributes to understanding supermassive black hole (SMBH) formation and evolution, and galaxy-SMBH co-evolution, with great relevance for gravitational-wave (GW) experiments. Our findings, consistently with simulations, suggest that galaxy interactions and mergers are likely to induce perturbations that enable the gas to be funneled towards the central nuclear regions and to be accreted efficiently, thus increasing the amount of absorption at close pair separations and possibly the AGN luminosity. We introduced innovative selection techniques, such as the Gaia Multi Peak method, to identify kpc-scale dual AGN beyond the low-redshift Universe, and we addressed challenges in detecting obscured dual AGN. As for binary systems, we identified two highly promising candidates exhibiting possible X-ray periodicity and, in one case, a potential double-peaked iron emission line.

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1. Introduction

Observational data reveal that the most massive galaxies harbor SMBHs (M_{BH}>10^6 $M_{\odot}$), whose properties are suggestive of a close connection with galaxy evolution [11]. The ΛCDM cosmological paradigm suggests hierarchical galaxy evolution through mergers, resulting in the widespread occurrence of pairs of SMBHs at relative kpc/sub-kpc distances, designated as dual SMBHs. Theoretical models and simulations [e.g., 12–15] propose that major galaxy mergers efficiently remove angular momentum, thus enabling substantial gas inflows toward the nuclear regions of galaxies, fostering star formation (SF) and triggering nuclear activity; this process would then lead to the formation of dual AGN. Due to dynamical friction induced by stars and gas, the two AGN are subsequently drawn to the center of the remnant galaxy [16], forming gravitationally bound binary AGN at pc/sub-pc scale separation; these constitute a relevant source of low-frequency GWs.

The investigation of dual and binary AGN systems holds paramount significance in advancing our understanding in the field of hierarchical structure formation and growth and demographics of SMBHs. Even more compelling, SMBH binary systems have a high relevance for the current and future GW experiments (PTA [17, 18]; LISA, [19]; and LGWA [20] for lower mass AGN).

In recent years, we started a wide-ranging project focused on the identification and physical characterization of dual and binary AGN at low and high redshifts. The primary objectives of the program include: (1) investigating the statistical properties of known dual AGN, mostly at kpc-scale separations, (2) identifying new samples of kpc/sub-kpc scale dual AGN, extending observations to higher (z>0.5) redshifts, and (3) selecting new and promising candidates for binary AGN (pc/sub-pc scale). A brief review of some of the results obtained so far is provided in the following sections.

2. Dual AGN: pair separation from a few kpc up to 100 kpc

With the primary aim of characterizing a homogeneous sample of dual AGN at kpc separations in the early stages of mergers and comparing their properties with those of isolated AGN, we conducted an extensive study of the sample of [21]. This dataset comprises over a thousand pairs of AGN spectroscopically selected from the SDSS, spanning a wide range of relative spatial separations (from a few kpc up to 100 kpc), with an average redshift of z~0.1. The sample selection, multi-band (X-ray, optical, and mid-infrared) analysis, and results are comprehensively reported in [8] and briefly summarized in the following.

About 300 optical sources from [21] fall in the sky regions covered by XMM-Newton and Chandra observations. Cross-correlation of their positions with the XMM-Newton and Chandra catalogs [22, 23] allowed us to find 26 X-ray emitting dual systems (i.e., 52 individual sources), for which mid-infrared data are available from the AllWISE catalog [24]. We conducted a comprehensive study involving the re-analysis of optical spectra through the Baldwin, Phillips & Terlevich (BPT; [25]) diagram, which utilizes the intensities of different lines for source classification as either AGN or SF galaxies. Then we adopted the X-ray to mid-infrared flux ratio versus the X-ray colors diagnostic diagram proposed by [26] to provide a broad classification of the sources into obscured AGN, unobscured AGN, and SF-dominated galaxies. We then combined the results found by the X-ray–mid-infrared diagnostic diagram with those coming from the X-ray spectral analysis to derive the fraction of obscured AGN in our sample.

The multi-band analysis validates the AGN classification for 80% of the sample; most of these are obscured AGN. Notably, AGN within pairs exhibit larger levels of obscuration compared to isolated AGN (about 80% vs. 45%; see also [27]), and both intrinsic obscuration and luminosity show an increasing trend with decreasing pair separation. On a zeroth-order theoretical interpretation, in dual AGN the gas is likely to be transported close to the nuclear regions because of the efficient removal of angular momentum; this process originates an increased level of obscuration (Fig. 1, left panel) and boosts the AGN luminosity (Fig. 1, right panel).

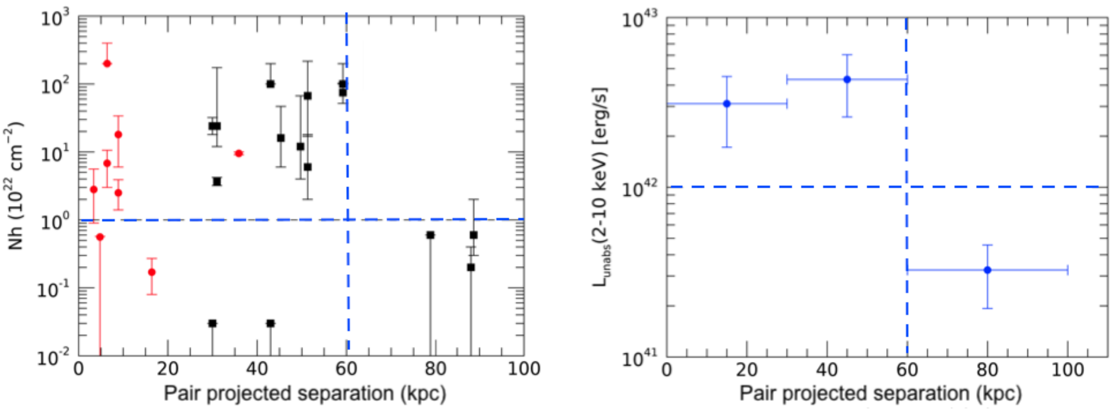

Figure 1: Intrinsic absorbing column density N_H (left panel) and unabsorbed X-ray luminosity (right panel) vs. pair projected separation for X-ray dual AGN. Black and red symbols in the left panel represent XMM-Newton and Chandra detections, respectively. The vertical dashed lines mark the 60 kpc separation (most of the recent studies were focused at separations below this value), while the horizontal dashed lines mark the "threshold" for obscured AGN (above 10^{22} cm^{-2}, left panel) and relatively luminous AGN emission (above 10^{42} erg s^{-1}, right panel). Adapted from [8].

3. Dual AGN: sub-kpc/kpc scale separation

The investigation of dual AGN in the late stages of mergers at kpc/sub-kpc distances (i.e., at tighter physical separations with respect to those described above) demands significantly enhanced angular resolutions to directly resolve the two nuclei through imaging. Currently, only a handful of dual AGN with such low pair separations are known at z>0.5 [28, 29]. A novel selection technique, named GMP – the Gaia (EDR3) Multi Peak method – was recently proposed by [6]. This method exploits the all-sky Gaia database and its excellent point-spread function (PSF) of 0.11" in the scan direction. Gaia observations of objects with G>16 mag consist of 1D projection along the scan direction of the signal in a 0.71"×2.1" window. The GMP method is based on the selection of all the Gaia sources showing multiple peaks in the light profile of the primary, brighter source. Through high-resolution – both archival and proprietary – photometric and spectroscopic follow-up observations (HST, Keck, LBT, and VLT data) of GMP sources, [7, 9, 10] successfully demonstrated that the GMP method can identify a substantial sample of high-redshift (z>0.5) dual AGN candidates at separations ranging from 0.15" to 1.2". To date, about 15 new dual AGN at 0.5<z<3 with pair separations below 10 kpc have been confirmed (see Fig. 2), unveiling new opportunities for studying the physical and evolutionary properties of dual AGN up to high redshift.

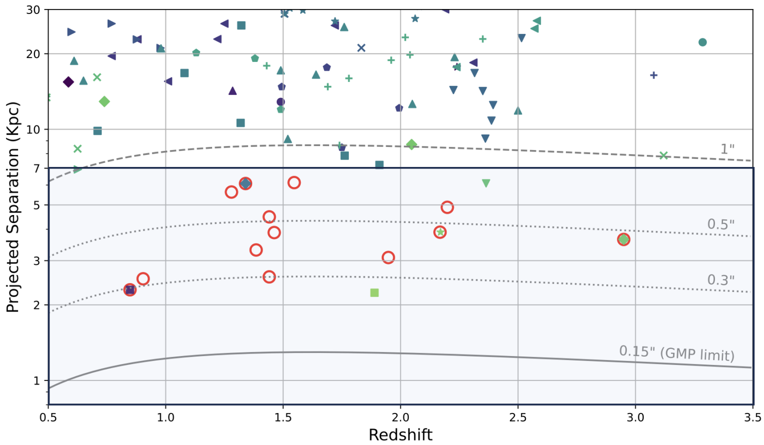

Figure 2: Projected separation vs. redshift of all spectroscopically confirmed dual AGN with separation below 30 kpc. Red circles denote the newly identified GMP dual systems, while other symbols correspond to those described in Fig. 6 of [7]. The shaded region mark the AGN with projected separations below 7 kpc, mostly occupied by GMP discoveries. Adapted from [7].

The GMP method is highly effective in identifying dual AGN with a low level of extinction, primarily due to its reliance on the G band selection.

The detection of obscured dual AGN at the sub-kpc/kpc scale is more challenging. Their current knowledge derives mostly from systematic investigations focused on the detection of double-peaked narrow optical emission lines associated with individual AGN. Double-peaked lines may arise from two distinct narrow-line regions (NLRs), each related to distinct – yet unresolved – AGN, hosted within the same galaxy. Approximately 2% of the SDSS AGN population exhibits double-peaked high-ionization emission lines [2, 30]. Unfortunately, various kinematics effects (other than the presence of a dual AGN) may yield double-peaked optical lines, e.g. outflow and NRL rotation of a single AGN. Therefore, to confirm double-peaked emission line sources as dual AGN, additional follow-up observations are required. This includes high spatial-resolution infrared imaging (where the effects of extinction are lower) enabling the detection of the two nuclei, followed by spatially resolved spectroscopy. However, thanks to dedicated adaptive-optics (AO) infrared observations carried out using LBT, we have demonstrated that even high spatial-resolution imaging may fail to resolve dual AGN in the presence of substantial intrinsic obscuration [4] since, in this case, the double nuclei are completely overwelmed by the host galaxy emission. To avoid missing a significant fraction of dual systems, an effective search for dual AGN among double-peaked emission-line sources requires both sub-arcsec resolution imaging and a careful subtraction of the host galaxy contribution.

4. Binary AGN candidates: the last step before the encounter

For these compact systems, direct imaging is currently unfeasible due to limitations in angular resolution posed by existing facilities, except for high-resolution interferometric observations of radio-emitting sources (see, e.g., [31–33], but also see [34]). For radio-quiet sources, only indirect methods can be employed. Following theoretical predictions, a fraction of the gas in the central region of the merging galaxy may reach the vicinity of the SMBHs, leading to the formation of a circumbinary accretion disc around the SMBH binary system. Gravitational torques acting on the inner edge of the circumbinary disc induce periodic inflows of mass, subsequently fueling mini-discs around each of the two SMBHs (e.g., [35]). In such a scenario, the dynamics of the system, along with other effects due to the orbital motion of the two SMBHs, should produce periodicity in the optical and X-ray light curves. In addition to the continuum, several sets of emission lines are expected, as in typical AGN. Specifically, in the X-ray band, two 6.4 keV fluorescence iron (Fe Kα) emission lines should be generated by the reflection of X-ray photons up-scattered in the corona. This reflection can occur at the surface of the mini-discs, at the circumbinary disc, or in the medium between the two black holes and the circumbinary disc. Due to the orbital motion of the two black holes, the two emission lines are expected to show variability in both intensity and energy.

In the last few years, we have been searching for AGN with periodic X-ray flux variations and/or double-variable Fe Kα emission lines. We found two promising AGN binary candidates in the local Universe, namely Mrk 915 and MCG+11-11-032. Both sources show possible periodic X-ray flux variability on a time scale of years (~35 months for Mrk 915 and ~25 months for MCG+11-11-032) which, in the case of SMBH binary systems, would imply milli-pc separations and estimated coalescence times of ~1.5 Myr and ~3.3×10^4 yr for Mrk 915 and MCG +11-11-032, respectively [1, 3, 5]. The latter system shows also a tentative detection of a double-peaked Fe Kα emission line, with a Δv (as measured from the Swift-XRT spectrum; see Fig. 3) consistent with its X-ray-derived period (see, [1] for further details). A long-term X-ray monitoring to catch possible variability in the energy and intensity of the two emission lines is ongoing.

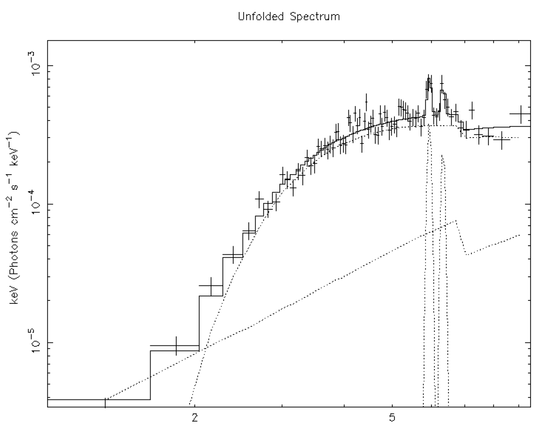

Figure 3: Unfolded Swift-XRT spectrum of MCG+11-11-032 (observed-frame) fitted with a model comprising an intrinsically absorbed power law plus a continuum reflection component and two narrow emission lines (at rest-frame energies E~6.16 keV and 6.56 keV). While the detection of the 6.56 keV emission line remains tentative (2σ significance), the 6.16 keV line is observed with higher significance (more than 3σ) and is not consistent with the rest-frame Fe Kα emission line at the 97% confidence level. Adapted from [1].

5. Summary and follow-up programs

Our program is dedicated to identifying and characterizing dual and binary AGN as they progress towards coalescence and GW emission. In this paper, we briefly reviewed some of the main results found so far by our collaboration.

We set some statistical properties for dual AGN in the early stages of mergers. Consistent with theoretical models, we found that dual AGN are hosted in environments where gas is conveyed close to the AGN, thus providing obscuration towards the nuclear sources and fuel supporting an increased X-ray luminosity. We addressed important challenges in identifying and studying dual AGN in the late stages of the merger, in particular for what concerns highly obscured AGN. We proposed a novel technique (the GMP method), exploiting the GAIA sky coverage and its excellent PSF, to uncover and study less obscured pairs of AGN at kpc separations over a broad redshift range (z~0.5–3). Through this method and follow-up spectroscopic programs, valuable insights into the prevalence and physical properties of dual AGN will be derived. Dual AGN represent the most direct precursors of AGN binaries, the last phase before SMBH coalescence. Binary AGN could be indirectly unveiled through periodic variability and double/broad emission lines. In this regard, we are currently studying two of the most promising AGN binary candidates showing possible X-ray periodicity and, in one case, a potential double-peaked iron emission line, due to the orbital motion of the two SMBHs.

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DISCUSSION

MARIO BACHETTI: How did you determine the periodicity for Mrk 915?

PAOLA SEVERGNINI: We estimated the periodicity of Mrk 915 by examining the Swift-BAT (Burst Alert Telescope) 105-month catalog. To be more specific, Serafinelli et al. (2020) identified a possible periodic signal (~35 months) in the X-ray light curve of Mrk 915 through the power-spectrum analysis and sinusoidal fitting of the 105-month BAT light curve. This finding was supported by the epoch-folding procedure, concluding that the non-periodic hypothesis can be rejected at the 3.7σ confidence level.

HERMAN MARSHALL: What are the rest-frame energies of the two features in the X-ray spectrum of MCG+11-11-032? Will you be re-observing this target to see if the two lines are shifting?

PAOLA SEVERGNINI: The rest-frame energies are at about 6.16 keV and 6.56 keV. An X-ray monitoring is currently on-going to investigate possible variations in the line energies (and intensities).