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Supermassive Black Hole Binaries and dual AGN

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Abstract. The search for supermassive black hole (SMBH) binaries at sub-pc scale separation and dual active galactic nuclei (AGN) at kpc separations are among the hottest topics of current theoretical and observational astrophysics, given their relevance in understanding the hierarchical structure formation and the growth of SMBHs. Even more compelling, binary SMBHs are loud emitters of gravitational waves in the low-frequency ranges. We report here our recent results on two of the most promising SMBH binary candidates uncovered through observations in the X-ray band, and on one of the few sub-kpc dual AGN discovered so far.

Key words. Galaxies: active – Galaxies: interactions – Galaxies: Seyfert – X-rays: galaxies – Dual and binary AGN – Black hole physics – Galaxies: individual: MCG+11-11-032 – Mrk 915 – SDSS J143132.84+435807.20

1. Introduction

Following the current ΛCDM cosmological paradigm, galaxies grow hierarchically through mergers (e.g. White & Rees 1978; Springel et al. 2005). Since the majority of galaxies should harbour a central supermassive black hole (SMBH, $M_{\rm BH} > 10^6\ M_\odot$), binary SMBHs (sub-pc and pc separations) are expected to be common in the Universe (e.g., Colpi 2014). The surrounding gas can accrete onto each of the SMBH components (see Dotti et al. 2007) emitting electromagnetic (EM) signals (active phase). The search for and the characterization of binary SMBHs through EM observations are among the most interesting and debated topics of modern astrophysics. They allow us to infer crucial information about the assembly of galaxy bulges and the origin of SMBH mass-bulge scaling relations. Since binary SMBHs are also powerful sources of gravitational waves (GW), these systems are critical for current and upcoming low-frequency GW experiments, such as the Pulsar Timing Arrays (PTA, Verbiest et al. 2016), and to predict the merger rate in higher-frequency experiments, such as the Laser Interferometer Space Antenna (LISA, Amaro-Seoane et al. 2017) and the Lunar Gravitational Wave Antenna (LGWA, Harms et al. 2021).

Unfortunately, direct observations of binary SMBHs is still a challenging task since their angular separations are much smaller than the spatial resolutions of current facilities; the only possible exceptions are radio-loud objects, which can be observed using the very long baseline interferometry (VLBI) technique (see, e.g., Rodriguez et al. 2006; Kharb et al. 2017; Deane et al. 2014). So far, only a few promising binary SMBH candidates have been discovered (see, e.g., Valtonen et al. 2008; Boroson & Lauer 2009; Tsalmantza et al. 2011; Eracleous et al. 2012; Decarli et al. 2013; Ju et al. 2013; Shen et al. 2013; Graham et al. 2015; Runnoe et al. 2017; Wang et al. 2017; Severgnini et al. 2018; Serafinelli et al. 2020; Saade et al. 2020; O'Neill et al. 2022; Jana et al. 2021; Jiang et al. 2022).

Hydrodynamical simulations show that dense gas in the central region of the host galaxy forms a circumbinary disk around the binary SMBH system, while accretion will occur by means of two mini-disks, surrounding each SMBH (see, e.g., d'Ascoli et al. 2018; Tang et al. 2017). This will produce periodicity in the emitted luminosity which is expected to be modulated by the orbital period of the two SMBHs (Hu et al. 2020, and references therein). Since UV radiation and X-rays originate very close to each black hole, these EM bands are considered the best ones for searching for periodicity from binary SMBH system candidates (e.g., Sesana et al. 2012). In particular, the X-ray band is optimal because it is less affected by gas absorption along the line of sight (e.g. Severgnini et al. 2018). Additionally, as binaries enter their inspiralling phase dominated by GW emission, they inevitably induce double-peaked iron emission lines in X-rays, whose energies are Doppler-shifted by the mini-disk orbital motion (Sesana et al. 2012; Popović 2012; McKernan & Ford 2015).

Since direct imaging is unfeasible, indirect methods based on the observational signatures discussed above have been pursued to detect binary SMBHs. In particular, by exploiting the potential of the *Swift* data archive, our team has recently conducted a systematic investigation, which led to the discovery of two of the most promising binary SMBH candidates to date (MCG+11-11-032 and Mrk 915, see Severgnini et al. 2018; Serafinelli et al. 2020). These works are outlined in more details in Sect. 2.

In addition, we are starting a project to find dual Active Galactic Nuclei (AGN) at sub-kpc scale separation (Severgnini et al. 2021); they represent the direct precursors of binary SMBHs. Being observationally more accessible than binary SMBH systems, sub-kpc dual AGN represent the most promising way to estimate the binary SMBH incidence.

The results on sub-kpc dual AGN obtained by our group are summarized in Sect. 3, while conclusions are reported in Sect. 4. Throughout the paper, we assume a flat ΛCDM cosmology with H_0=69.6 km s^{-1} Mpc^{-1},

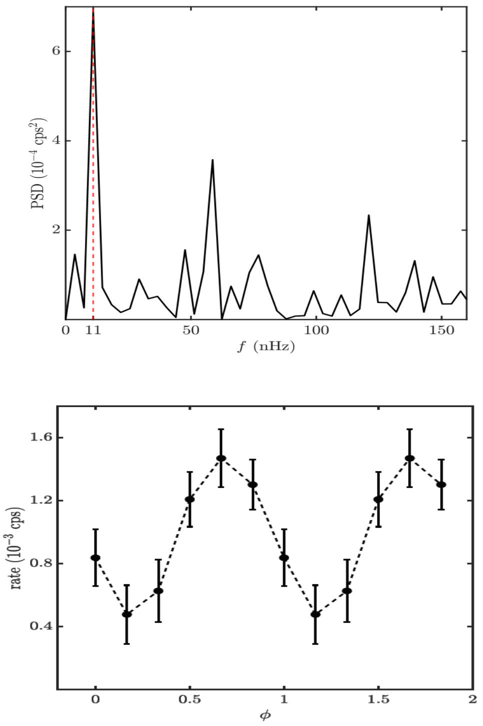

Fig. 1. Adapted from Serafinelli et al. (2020). Upper panel: Power spectral density of Mrk 915. The red vertical dashed line represents the harmonic peak at $f_0\sim11$ nHz which corresponds to an observer-frame period of about 35 months. Lower panel: Phase-folding of the *Swift*-BAT 105-month light curve of Mrk 915 (a period of 35 months was assumed).

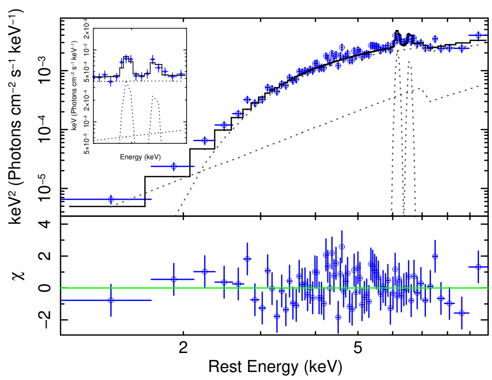

Fig. 2. Adapted from Severgnini et al. (2018). Upper panel: the model including an intrinsically absorbed power law ($\Gamma\sim1.7\pm0.2$, $N_{\rm H}$=[1.3±0.1] $\times10^{23}$ cm^{-2}) plus a continuum reflection component and two narrow emission lines are overplotted onto the unfolded XRT spectrum of MCG+11-11-032. The zoomed part of the spectrum covering the two emission lines is shown in the box. Lower panel: Data−model residuals, plotted in units of σ.

Ω_λ=0.7 and Ω_M=0.3. Errors are given at the 68 per cent confidence level unless otherwise specified.

2. Sub-pc binary SMBH candidates

As discussed above, although binary SMBHs are a natural outcome of galaxy mergers, only few of them have been discovered and studied so far (see De Rosa et al. 2019).

2.1. Mrk 915

By considering the *Swift*-BAT (Burst Alert Telescope) 105-month catalogue, we have recently proposed a new method to select binary SMBHs based on the detection of a periodic signal in their X-ray light curves. By using the Fisher's exact g-test and taking into account the possible presence of colored noise, we found a very promising binary SMBH candidate, Mrk 915 (z=0.024). The power spectrum analysis and the sinusoidal fit of the 105-month BAT light curve revealed a periodic modulation in the 14–195 keV emission, with a period of ∼35 months (Fig. 1, upper panel). We tested this period with an epoch-folding procedure (Fig. 1, lower panel), finding that the null (i.e. non-periodic) hypothesis can be rejected at the 3.7σ confidence level. Assuming a Keplerian orbit and a SMBH mass of $\sim10^8$ $M_\odot$ (Bennert et al. 2006), we derived a distance of $\sim5\times10^{-3}$ pc between the two hard X-ray-emitting sources. Assuming a circular orbit, the relative velocity between the putative black holes is $v\sim0.034$c (Serafinelli et al. 2020).

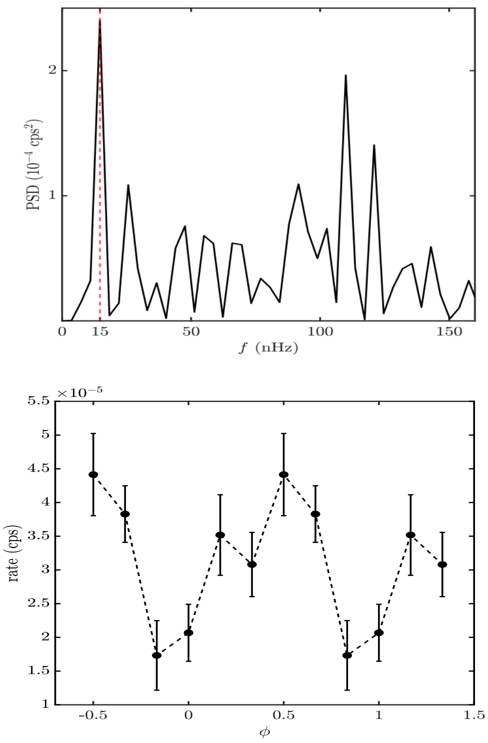

Fig. 3. Adapted from Serafinelli et al. (2020). Upper panel: Power spectrum of the *Swift*-BAT light curve of MCG+11-11-032. The harmonic peak at f_0~15.5 nHz corresponds to an observer-frame period of about 26 months. Lower panel: Phase-folding of the *Swift*-BAT 123-month light curve of MCG+11-11-032 (a period of 26 months was assumed).

2.2. MCG +11-11-032

The only previously X-ray selected binary SMBH candidate is the Seyfert 2 galaxy MCG+11-11-032 (z=0.0362). The discovery that this source could actually host two close SMBHs came from the combined analysis of *Swift* X-Ray Telescope (XRT) and BAT data (Severgnini et al. 2018). In the XRT spectrum, we did not detect a single Fe Kα emission line at the expected rest-frame energy of 6.4 keV (in case of neutral iron). Instead, we detected two unexpected emission lines (see Fig. 2) at rest-frame energies of E_1=6.16±0.08 keV (EW~120 eV, $F_{\rm line1}$~8×10^{-14} erg s^{-1} cm^{-2}) and E_2=6.56±0.15 keV (EW~85 eV, $F_{\rm line2}$~6×10^{-14} erg s^{-1} cm^{-2}). Neither of the two XRT detected lines is clearly associated with well-known and expected transitions. One possible intriguing hypothesis is that they may be induced by the presence of a binary SMBH. Assuming that the system is observed edge-on, the corresponding velocity offset derived by the rest-frame ΔE is Δv~0.06c.

A visual inspection of the BAT light curves supports the presence of almost regular peaks and dips every 25-26 months (Severgnini et al. 2018). In the scenario where two SMBHs are present, considering a total SMBH mass of ~5×10^8 $M_\odot$ (Lamperti et al. 2017), the observed modular behavior would imply a sub-pc separation (about 6.5×10^{-3} pc) between the two SMBHs, with an orbital velocity of Δv~0.06c. Quite strikingly, the Δv value is consistent with that estimated through the two Fe emission lines.

In Serafinelli et al. (2020), we present a detailed timing analysis of the 105-month and 123-month BAT light curves of MCG+11-11-032 which produced results consistent with Severgnini et al. (2018). From the power spectrum analysis and the fit of the light curves, we tentatively confirmed a rest-frame period of 26^{+4}_{-2} months (Fig. 3, upper panel). By adopting this period, we performed the epoch folding of both the 105-month and the 123-month BAT light curves of MCG+11-11-032 and found that the null hypothesis is rejected at the 2.6σ confidence level (Fig. 3, lower panel). Considering also the result in Severgnini et al. (2018) in the combined probability test (see Eq. 2 in Serafinelli et al. 2020), the null hypothesis can be rejected at the 2.9σ (3.5σ) confidence level when the 105-month (123-month) light curve is used.

2.3. Coalescing time

Assuming circular motion, we estimated a coalescing time due to GW emission through the expression by Peters (1964), i.e.

$$T_{\rm gw} = \frac{5c^5(1+q)^2a^4}{256G^3M^3q} \qquad (1)$$

Here M, q, a are the total mass, the mass ratio and the semi-major axis of the binary. When considering an equal mass SMBH binary (q = 1), the estimated time to coalescence yields $\approx$ 1.5 Myr for Mrk 915, while about 3.3×10^4 yr for MCG +11-11-032.

3. Sub-kpc dual AGN candidate

Sub-kpc dual AGN would provide an unbiased view of SMBHs and galaxies in the final stages of the merging process. For this reason, several systematic investigations have been conducted to search for sub-kpc dual AGN candidates in the last decade (see e.g., De Rosa et al. 2019, for a detailed review). Many of these studies are based on the quest for double-peaked narrow optical emission lines originating from two distinct narrow-line regions (NLRs). Unfortunately, once a suitable sample of double-peaked emission-line AGN (hereafter DPAGN) has been selected (e.g. Wang et al. 2009; Smith et al. 2010; Liu et al. 2010; Ge et al. 2012), only a small number of them (less than 15) has been confirmed as sub-kpc dual AGN through high spatial resolution observations (see e.g. Voggel et al. 2022, and references therein). As a result, the fraction of sub-kpc dual AGN confirmed so far in the local Universe is roughly one order of magnitude lower than model predictions (e.g., Foreman et al. 2009). However, as argued in our recent paper (Severgnini et al. 2021), some of the previous studies on DPAGN may have missed a significant fraction of dual AGN because most of then can be obscured and completely overshadowed by the host galaxy.

In Fig. 4 we report our recent result obtained for one local (z=0.096) double-peaked type 2 AGN observed in the K band using the Large Binocular Telescope (LBT) LUCI2 camera (Seifert et al. 2003) with the First Light Adaptive Optics system (FLAO, Esposito et al. 2012) in diffraction-limited mode. The target, SDSS J1431+4358, appears as a single bulge-dominated galaxy in the total sub-arcsec K-band imaging (panel A), while two cores (~0.4 kpc separation) are clearly unveiled after subtraction of the host galaxy contribution (panel B). Accordingly to the results obtained

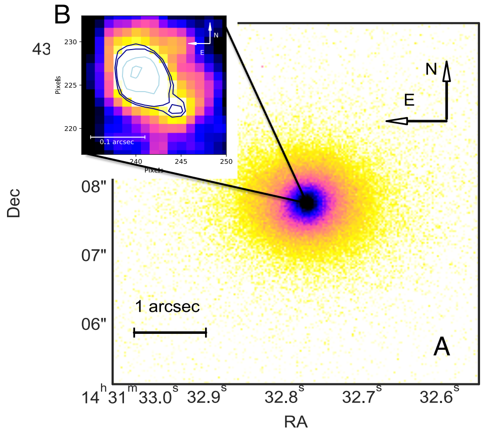

Fig. 4. Adapted from Severgnini et al. (2021). Images of the dual AGN candidate SDSS J1431+4358 (type 2 AGN with double-peaked emission lines; z=0.096) obtained using the LBT LUCI+FLAO NIR camera. Panel A: Zoomed (5”×5”) LUCI2+FLAO K-band image ($K_{\rm Vega}$ ~13.8 mag). The observations were performed under a natural seeing condition of 0.7”, and an image quality with a full width at half maximum of 0.15” was obtained. Panel B: Nuclear region (0.24”×0.24”) after the subtraction of the host galaxy contribution.

by analyzing both the SDSS and the XRT spectra, the cause of the apparent faintness of the two nuclei is the large amount of intrinsic obscuration affecting the continuum emission in the central nuclear region (see Severgnini et al. 2021, for details on the analysis of the optical, infrared and X-ray data).

4. Conclusions

The detection and study of dual sub-kpc AGN and binary SMBHs are still in a pioneering age. In particular, the search for binary SMBHs is still a completely open challenge. As shown in Severgnini et al. (2018) and Serafinelli et al. (2020), X-ray observations are one of the most promising tools to identify these systems, at least in the case of radio-quiet sources. While long-term X-ray monitoring allows us to investigate the presence of modular behavior, high-quality X-ray spectra permit to unveil double Fe Kα emission lines. In this context, a new window in the search for double-peaked Fe

Kα lines will be opened by the microcalorimeters on board future X-ray observatories, such as XRISM (XRISM Science Team 2020) and Athena (Barret et al. 2016).

For what concerns sub-kpc dual AGN, although the DPAGN technique should provide an unbiased sample of candidates, very few sources have been confirmed so far, and their observed incidence is still too low when compared with theoretical expectations. In Severgnini et al. (2021), we found that, due to the strong obscuration affecting these systems, an appropriate search for dual AGN requires sub-arcsec resolution IR imaging (where the effects of extinction are lower), coupled with the subtraction of the host galaxy contribution. In addition to the discovery of the new sub-kpc scale dual AGN candidate hosted in SDSS J1431+4358, we suggested that the fraction of dual sub-kpc scale AGN among DPAGN could actually be considerably much higher than what inferred by previous studies.

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