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Short Communication

A jetted wandering massive black hole candidate in a dwarf galaxy

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Dwarf galaxies, with their shallow gravitational potentials, less evolved assembly histories, and low mass, serve as critical laboratories for studying massive black hole (MBH) formation and growth [1]. They preserve signatures of the primordial processes that shaped early MBH emergence [2]. Off-nuclear (or offset) active galactic nucleus (AGN) are increasingly recognized as important laboratories for understanding galactic dynamics and black-hole evolution, with recent studies indicating that they are quite common in various galaxy populations. For instance, systematic surveys using optical spectroscopy, X-ray, and integral field unit (IFU) observations have identified spatially or kinematically offset AGNs in 2%–62% of samples, depending on methodology [3–5]. Regarding AGNs with offset radio cores, Popkov et al. [6] identified ~ 35 cases where very long baseline interferometry (VLBI) coordinates are associated with bright jet components separated by several to tens of milliarcseconds (mas) from the radio core. The primary mechanisms for such off-nuclear AGNs include dual/binary supermassive black holes (SMBHs) and jet-driven displacements, though systems hosted in dwarf galaxies remain rare and more complex due to their shallow potentials and merger histories. The discovery of off-nuclear MBHs challenges traditional evolutionary models that typically posit nuclear gas reservoirs as the primary sites of MBH growth. MBH displacement from the galactic centre can result from gravitational wave recoil during mergers or asymmetric gas accretion [7]. Recoil velocities can even exceed the escape velocities of dwarf galaxies. Numerical simulations indicate that approximately 50% of MBHs in dwarf galaxies might reside more than 1 kiloparsec (kpc) from their hosts' centre [8], a prediction consistent with current observations [5,9].

However, detecting these displaced MBHs remains challenging, particularly in low-mass systems where shallower gravitational potentials increase their likelihood of ejection. The Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) survey has advanced AGN detection in dwarf galaxies through spaxel-by-spaxel emission-line analysis, surpassing the traditional single-fiber spectroscopy limitations. Using spatially resolved Baldwin-Phillips-Terlevich (BPT) diagnostics with [N II], [S II], and [O I] line ratios, MaNGA has identified AGN candidates in 628 dwarf galaxies [5,10]. Notably, 62% of these systems show offsets $\geqslant 3$ arcseconds ($''$) between AGN-dominated spaxels and the galactic centre. At $z \sim 0.03$, MaNGA's resolution of about 1 kpc allows differentiation between three scenarios: light echoes from past AGN flares, wandering intermediate-mass black holes (IMBHs) displaced by dynamical interactions, and obscured low-accretion AGNs [11]. Recent extended ROentgen Survey with an Imaging Telescope Array (eROSITA) X-ray data [12] corroborated with MaNGA findings and theoretical predictions, reveals that roughly 50% of eROSITA-detected AGNs are spatially off-nuclear.

However, strong emission from H II regions in star-forming dwarfs often obscures AGN optical signatures, with [O III]/Hβ ratios mimicking AGN excitation [13]. Ultraluminous X-ray sources (ULXs) can also imitate AGN variability, hindering X-ray diagnostics. Radio observations, especially VLBI, prove invaluable by detecting compact cores with brightness temperatures ($T_b > 10^9$ K), exceeding star-forming maxima ($\sim 10^7$ K) [9].

Recent Very Long Baseline Array (VLBA) observations of 13 radio-selected dwarf galaxy candidates detected four compact mas-scale structures in galaxy outskirts with $T_b > 10^6$ K [14],

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consistent with AGN but likely background sources due to large offsets. Remaining sources could have extended radio emission on scales of tens of parsecs, which could originate from supernova remnants or AGN-powered radio lobes [15].

Previous surveys lacked the astrometric precision needed to unambiguously associate compact radio sources with dwarf galaxies, leading to significant background contamination [14]. Optical and X-ray diagnostics also struggle to separate faint AGN from ultraluminous X-ray binaries in galaxy outskirts [16]. Finally, only a few off-nuclear MBHs with sustained accretion have been confirmed, limiting our understanding of early black-hole growth. Although recent observations have expanded the census of AGN candidates in dwarf galaxies [17], VLBI confirmations remain scarce.

We address these challenges by presenting compelling, multifaceted evidence for an off-nuclear AGN candidate in the dwarf galaxy MaNGA 12772–12704 using VLBI (Fig. 1a and b). The MaNGA IFU observations [5] reveal that this galaxy exhibits AGN-like line ratios, with emission lines falling within the Seyfert and LINER regions of the $\log([\mathrm{O\,III}]/\mathrm{H}\beta)$ versus $\log([\mathrm{O\,I}]/\mathrm{H}\alpha)$ diagnostic diagram (Fig. 2a–d). Shown in the optical imaging Fig. 2e, the host galaxy exhibits no visible signs of merger activity, such as tidal tails, double nuclei, or external disturbances, supporting the interpretation of the radio source as a wandering black hole rather than a secondary AGN in a merging system. Additionally, the MaNGA spectral analysis shows the weak optical AGN emission-line region covering the radio core area, while the galaxy centre spaxel does not exhibit separated high-excitation line ratios. This finding further reinforced the off-nuclear AGN scenario over the dual-AGN interpretation. The absence of He II λ4686 emission in the AGN-dominated spaxels is unsurprising, as this line is typically weak and detected in only a small fraction of AGNs, particularly in low-luminosity systems such as the one studied here [13]. Adopting a stellar mass[1] of $M_{\mathrm{stellar}} = 1.52 \times 10^9\,M_\odot$, we estimate the black-hole mass $\log_{10}(M_{\mathrm{BH}}/M_\odot) = 5.54 \pm 0.45$ utilizing the $M_{\mathrm{BH}} - M_{\mathrm{stellar}}$ scaling relation [18]. The quoted uncertainty accounts for errors in stellar mass, the scaling relation parameters, and the relation's intrinsic scatter.

We carried out deep, high-resolution radio observations of MaNGA 12772–12704 using the VLBA at L band (1.6 GHz) and C band (4.9 GHz) on 13 and 14 February 2023, respectively. The observations were designed to astrometric precision of approximately 0.1 mas and resolve the radio emission structure. We accumulated ~ 1 h of integration time at each band, employing rapid phase-referencing cycles between the target source and a nearby calibrator to mitigate phase errors in the visibility data. A detailed astrometric analysis presented in Supplementary material confirms a separation of $2.68'' \pm 0.47''$ between the VLBI radio core (peak feature) and the optical galaxy centre, corresponding to a projected physical offset of (0.94 ± 0.16) kpc.

Our VLBA observations (Table S1 (online)) yield compelling evidence for a jetted AGN: the 4.9 GHz images reveal a compact radio core with a peak flux density of $(0.4 \pm 0.04)\,\mathrm{mJy\,beam^{-1}}$ and a brightness temperature $T_{\mathrm{b}} > 1.8 \times 10^9$ K, exceeding the values can be attributed to star formation by orders of magnitude. At 1.6 GHz, a resolved structure extends approximately (6.2 ± 0.4) mas (~ 2.2 pc) southeast (PA $\sim 134^\circ$), interpreted as a compact jet due to its alignment with the core and elongation morphology. The overall radio spectrum is steep ($\alpha \approx -1.2$, where $S_\nu \propto \nu^\alpha$), with the jet showing $\alpha_{\mathrm{jet}} \approx -2.0$ (optically thin synchrotron emission) and the core showing $\alpha_{\mathrm{core}} \approx -1.5$, typical of low-luminosity AGNs.

Archival Very Large Array (VLA) data (1993–2023, at frequencies of 1.4–1.5 GHz and 3 GHz) exhibit significant flux density variability (Fig. 1c and Table S2 (online)). The measured flux densities show variations: the 1.5 GHz flux density rose from (1.21 ± 0.15) mJy (2002) to (1.93 ± 0.10) mJy (2008), $\sim 4.6\sigma$ significance; then later 3-GHz measurements declined from (0.93 ± 0.10) mJy (2017) to (0.63 ± 0.15) mJy (2023). The prolonged flux density variability observed over a 30-year period is another key indicator of sustained accretion activity. This non-monotonic, decadal variability indicates sustained accretion, incompatible with SNR monotonic decay ($\sim$years timescale) [19]. Such patterns firmly support an AGN origin over transients.

The radio source in MaNGA 12772–12704 exhibits hallmarks of a jetted AGN: a compact core ($T_{\mathrm{b}} > 1.8 \times 10^9$ K), a parsec-scale jet, steep-spectrum emission, and decadal variability. Confined to $2.68'' \pm 0.47''$ (corresponding to (0.94 ± 0.16) kpc) at the source's redshift, it is offset from the galactic nucleus, marking the lowest-redshift ($z = 0.017$) VLBI-confirmed wandering AGN in a dwarf galaxy to date. Being the lowest-z source in the sample of Ref. [14] (ID6, J0106 + 0046), it escaped detection by the 9 GHz VLBA due to its steep spectrum and the sensitivity limits. This is unlike their four higher-z ($z > 0.02$) background AGN interpretations (> 2 kpc offsets), our source favors intrinsic association via: (1) smaller offset (< 1 kpc), (2) spatial coincidence between the radio core and the optical AGN emission-line region, and (3) sustained radio variability inconsistent with a background source (contamination probability $\ll 1\%$). This evidence collectively rules out superposition, supporting a displaced accreting MBH.

The identification of an actively accreting, off-nuclear MBH candidate in the dwarf galaxy MaNGA 12772–12704 challenges conventional black-hole growth models in low-mass galaxies, providing robust observational support for alternative accretion pathways. This has profound implications for early-Universe SMBH formation, AGN feedback, and black-hole demographics.

The 0.94 kpc offset of this accreting MBH challenges conventional black-hole growth models. Theory predicts that such wandering MBHs may arise from gravitational-wave recoil or asymmetric gas accretion [8]. Our VLBI detection of MaNGA 12772C12704 provides direct evidence that an intermediate-mass black hole can be spatially displaced from its hosts centre.

A recent example in a more massive galaxy is the offset tidal-disruption event AT2024tvd, where a black hole of about $10^6\,M_\odot$ lies ~ 0.8 kpc from the galaxy's central SMBH with a mass of about $10^8\,M_\odot$ [20]. Multi-epoch radio observations confirm ongoing accretion in that system. Together with the AT2024tvd example, our results suggest that black-hole growth may proceed away from galactic centres. Instead of relying solely on gas funnelled to the nucleus, wandering black holes can accrete distributed gas, providing an alternative pathway to rapid growth and enriching the diversity of AGN phenomena in dwarf galaxies.

The implications are profound especially for the SMBH formation in the early Universe, where traditional models struggle to explain the rapid growth of SMBHs to $\sim 10^9 M_\odot$ by redshift around 7 [21]. Traditional models assume continuous, efficient accretion fueled by gas funneled to the galactic centre. MaNGA 12772–12704 suggests an alternative pathway: black holes may grow through accretion events distributed throughout their host galaxy. This is particularly relevant in the gas-rich, chaotic galaxies in the early Universe. Instead of relying solely on central reservoirs, black holes could accrete ambient gas or merge with smaller ones. Such a model provides a more plausible pathway for rapid early SMBH growth, challenging the primacy of centralized accretion.

[1] The stellar mass value is derived from spectral energy distribution fitting of SDSS and GALEX photometry and listed in the NASA-Sloan Atlas (NSA catalog) version v1_0_1: https://www.sdss.org/dr17/manga/manga-target-selection/nsa/.

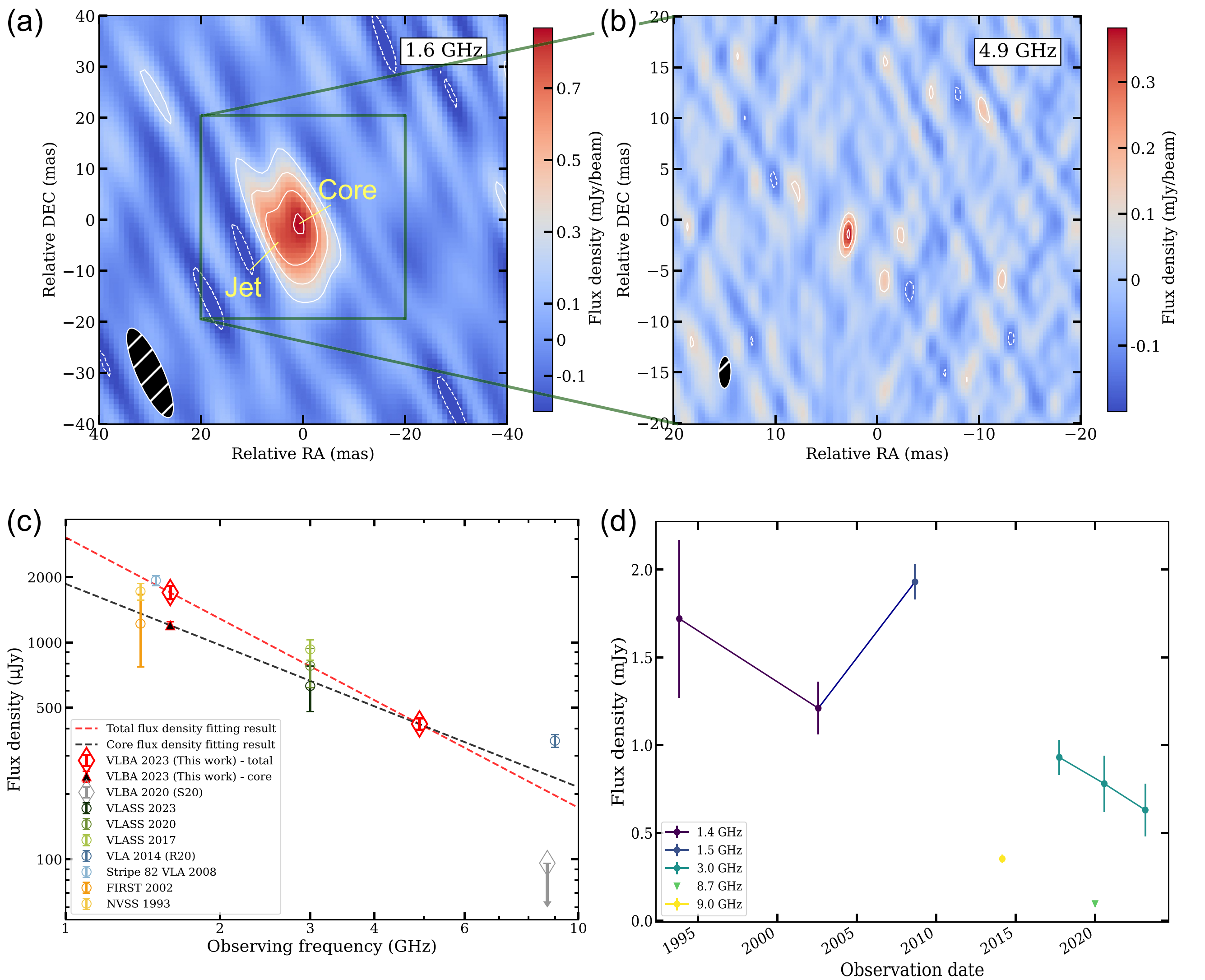

Fig. 1. VLBA images in L-band (1.6 GHz, panel (a)) and C-band (4.9 GHz, panel (b)), radio spectrum in panel (c), and multi-epoch and multi-wavelength flux density comparison in panel (d). Uniform weighting is used in creating both images. The contour levels are $(-1, 1, 2, 3, 4) \times 3\sigma$, in which the RMS noise is $1\sigma = 70$ and 40 μJy beam^{-1} for L and C band observations, respectively. The jet component is visible in the L-band image as an extension to the southeast of the core. The synthesis beam is shown in the lower left corner. In panel (c), the VLBA measurements from this work are represented by the red diamonds (total flux density) and triangles (core flux density). Other colored labels are from archive or literature VLA and VLBA data, listed in Table S2 (online). Both axes in panel (c) are on a logarithmic scale.

The presence of a compact ($\sim$ 2.2 pc) radio jet with a kinetic power of around 10^{41} erg s^{-1} emanating from the off-nuclear MBH prompts a re-evaluation of AGN feedback in low-mass galaxies. These observations suggest that even displaced MBHs can drive mechanical feedback, impacting star formation and gas dynamics within their host galaxies. The well-defined jet in this off-nuclear AGN shows that accretion disk-jet systems, commonly seen in powerful AGN within massive galaxies, can form and sustain beyond galactic centre, broadening our insights into AGN physics.

This discovery underscores the need for expanded strategies in searching for IMBHs, raising the question of whether MaNGA 12772–12704 is rare or indicative of a common, undetected population of wandering, accreting black holes. Addressing this requires next-generation facilities like the Square Kilometre Array (SKA) and next-generation Very Large Array (ngVLA), whose superior sensitivity and resolution will enable systematic surveys, probing fainter emissions and resolving finer structures in larger galaxy samples. For instance, SKA-mid could detect IMBH radio emission down to 10^{35} erg s^{-1}, while ngVLA's high-frequency capabilities resolve sub-parsec jet structures. These future observations could reshape black-hole demographics, mass distributions, growth mechanisms, early SMBH formation, and BH-dwarf galaxy co-evolution. MaNGA 12772–12704 glimpses the transformative insights ahead.

Conflict of interest

The authors declare that they have no conflict of interest.

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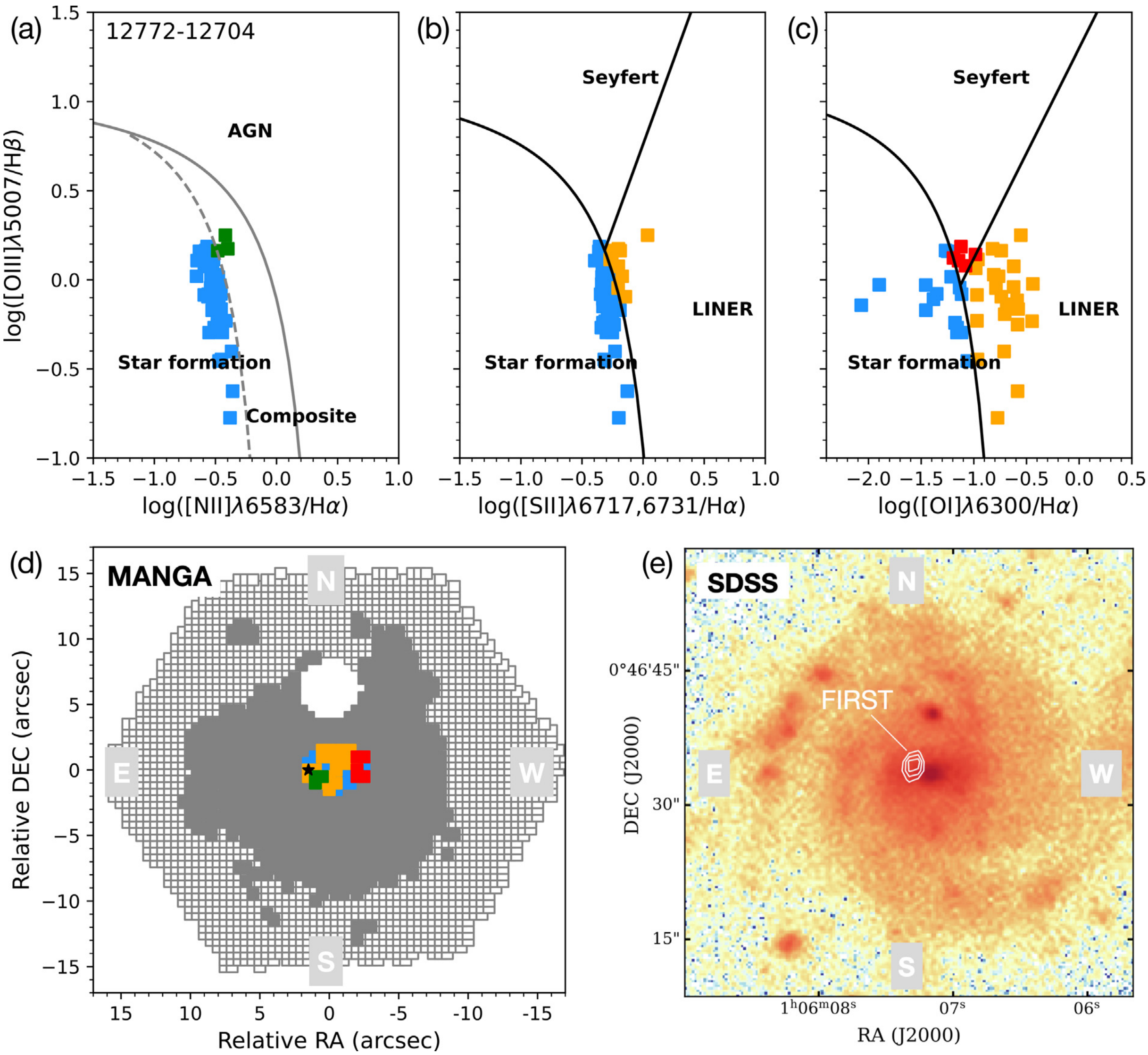

Fig. 2. Spatially-resolved BPT diagrams of MaNGA 12772–12704 and the optical image. The panels (a), (b), and (c) show BPT diagrams using different emission line ratios, revealing AGN, star formation, and LINER regions. The panel (d) plot shows the spatial distribution of ionization across the galaxy, while the panel (e) presents the SDSS *g*-band image overlaid with radio contours from FIRST survey indicating the off-nuclear source.

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Author contributions

Yuanqi Liu was responsible for data processing and analysis, and wrote the manuscript. Tao An conceived the overall research idea, supervised the project, and contributed to manuscript preparation. Yingkang Zhang and Jun Yang provided valuable guidance on VLBA data processing. Mar Mezcua collected and analyzed the optical data. Ailing Wang and Xiaopeng Cheng contributed to discussions and provided comments on the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.09.001.

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