Multiple supermassive black hole systems: SKA’s future leading role

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two primary messages:

1. multiple SMBH science will become mainstream with next-generation facilities

2. SKA will lead through broad range of techniques and perspectives
from the **galaxy evolution** viewpoint
galaxy mergers/interactions are a major observational focus
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dual/binary AGN are not (yet)
candidate dual/binary AGN in 2014
(from direct imaging)

squares = X-ray  triangles = optical/NIR  stars = radio

0402+379  3C75  NGC 326  NGC 6240  Mrk 739  Mrk 463  NGC 3393  SDSS J1715+6008  IRAS 05589+2828  SDSS J0952+2552  CID-42  LBQS 0103-2753  SDSS J1108+0659  SDSS J1131-0204  SDSS J1146+5110  SDSS J1332+0606  CXO J1426+35
candidate dual/binary AGN in 2004
(from direct imaging)

squares = X-ray  triangles = optical/NIR  stars = radio

- Chandra
- HST
- VLBI

- 3C75
- NGC 6240
candidate dual/binary AGN in 2014
(from direct imaging)

squares = X-ray  triangles = optical/NIR  stars = radio

0402+379  J1502S  3C75  NGC 326  NGC 6240  Mrk 739  Mrk 463  NGC 3393
IRAS 05589+2828  SDSS J1715+6008  SDSS J0952+2552  CID-42
LBQS 0103-2753  SDSS J1108+0659  SDSS J1131-0204  SDSS J1146+5110
SDSS J1332+0606  CXO J1426+35

triangles = optical/NIR
candidate dual/binary AGN 2014
(+ non-imaging)

squares = X-ray  
triangles = optical/NIR  
stars = radio

double-peaked BLR  ▲
optical variability  ▲

redshift

projected separation / parsec

0402+379
J1502S
3C75
NGC 326
NGC 6240
Mrk 739
Mrk 463
NGC 3393
SDSS J1715+6008
IRAS 05589+2828
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SDSS J1108+0659
SDSS J1113-0204
SDSS J1146+5110
SDSS J1332+0606
CXO J1426+35
SDSS 1536+0441
OJ287
candidate dual/binary AGN 2014
(+ non-imaging)

squares = X-ray  triangles = optical/NIR  stars = radio

Milky Way SMBH Schwartzchild radius
dual/binary AGN orbital evolution

<1 pc  ~10 pc  ~kpc

separation
dual/binary AGN orbital evolution

<1 pc  ~10 pc  ~kpc

separation

\textbf{dynamical friction}

1000s of examples
(e.g. Koss+2011, Liu+2011)
The page contains a presentation slide about dual/binary AGN orbital evolution. The slide includes a timeline showing different separations:

- Less than 1 pc
- Approximately 10 pc
- Kelvins (kpc)

The timeline describes the evolution of such systems, mentioning 'hardened' binaries with insprial driven by stellar 3-body interactions.

The slide highlights examples of dual AGN:
- **0402+379**: 7 pc (Rodriguez+2006)
- **NGC 3393**: 150 pc (Fabbiano+2011)
- **J1502S**: 138 pc (Deane+2014)

Additionally, it notes that 1000s of examples are available, such as in the work of Koss+2011 and Liu+2011.
dual/binary AGN orbital evolution

<1 pc  ~10 pc  ~kpc

gravitational radiation

`hardened' binary: in-spiral driven by stellar 3-body interactions

candidates from spectroscopic & periodic light curve signatures

(e.g. Valtonen+2008; Boroson & Lauer 2009)

0402+379 7 pc Rodriguez+2006

J1502S 138 pc Deane+2014

NGC 3393 150 pc Fabbiano+2011

1000s of examples (e.g. Koss+2011, Liu+2011)
`hardened' binary: in-spiral driven by stellar 3-body interactions

dynamical friction

pulsar timing (+ variability)

radio-jet morphology

direct imaging of flat-spectrum sources

separation 'coverage' with SKA
direct imaging

- flat-spectrum sources (with jets, multi-wavelength counterparts, etc.)
- image-splitting in lensing searches
- super-resolution with polarization
- SKA/radio will lead due to:
  - insensitivity to dust/gas attenuation
  - raw sensitivity
  - angular resolution
max GW frequency of SMBH binaries

assumes:
- binary SMBHs have angular separation = 2 PSFs
- circular orbits
- equal mass $10^8 M_\odot$ SMBHs

- $\sim 1$ day

- $\sim 30$ years

max GW frequency / Hertz vs. redshift

SKA Phase 2
SKA Phase 1
radio-jet morphology signatures
(aka "corkscrew relics")
Massive black hole binaries in active galactic nuclei

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Most theoretical discussions of active galactic nuclei (including quasars) attribute their energy production either to an accreting black hole or to a precursor stage—for instance a dense star cluster or a supermassive star—whose inevitable end point is a massive black hole. We explore here the possibility that some active nuclei may contain two massive black holes in orbit about each other. This hypothesis suggests a new interpretation for the observed bending and apparent precession of radio jets emerging from these objects and may indeed be verified through detection of the direct consequences of orbital motion.
a simple precessing jet model
(ala SS433)
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SS 433
credit: Blundell & Bowler, NRAO/AUI/NSF
~0.1 pc
A simple precessing jet model (ala SS433)

SS 433
credit: Blundell & Bowler, NRAO/AUI/NSF

~0.1 pc

SMBH binaries scaled up by 5-8 dex?
predicted binary SMBH in-spiral rates

binary separation evolves from 1 kpc to <1 pc in ~few 10s of Myr
predicted binary SMBH in-spiral rates

binary separation evolves from 1 kpc to <1 pc in \(\sim\) few 10s of Myr

comparable to radio jet lifetimes of \(\sim\) 10 Myr
radio-jet morphology signatures
(aka “corkscrew relics”)

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AASKA14
13/6/2014

radio-jet morphology signatures
(aka "corkscrew relics")
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<100 micro-arcsecond resolution
radio-jet morphology signatures
(aka “corkscrew relics”)

<100 micro-arcsecond resolution
stochastic GW background spectrum

- standard spectrum $\alpha = -2/3$ (assumes circular orbits)
- should change at ~10 nanoHz (when stellar scattering and gas dynamics dampen signal)
- binary eccentricity important in the nanoHz regime
- triple systems also lead to high eccentricities (via Kozai-Lidov mechanism) and recoiling/ejected SMBHs (Hoffman & Loeb 2007; Blecha+2011)
- therefore, very important to measure GW spectrum, not just single detection, from a galaxy evolution perspective to understand binary SMBH environment coupling
environment coupling
(with SKA and other facilities)

stellar `scouring'

mass deficits 1-10 times mass of SMBH binary
flattens inner density profile of galactic halo

molecular gas dynamics

NGC 1433 CO (3-2)
ALMA 24 pc spatial res.
Coombes+2013

HI emission and absorption

HI abs. in binary SMBH 0402+379
Rodriguez+2009, Morganti+2009

variability/transients

quasi-periodic accretion, light curves

Table 1

| Component | Amplitude (mJy) | Central Velocity (km s$^{-1}$) | FWHM (km s$^{-1}$) | $\tau_{\text{peak}}$ | $N_{\text{HI}}$ (cm$^{-2}$) |
|-----------|-----------------|-------------------------------|-------------------|---------------------|--------------------------|
| CW        | 2.8 ± 0.1       | 16,927 ± 7                  | 300 ± 20          | 0.025 ± 0.001       | (1.303 ± 0.006) × 10$^{21}$ |
| CE        | 1.5 ± 0.2       | 15,856 ± 9                  | 170 ± 20          | 0.018 ± 0.002       | (4.1 ± 0.1) × 10$^{20}$ |

Notes.

a CW and CE refer to the western and eastern jet components where we find absorption lines respectively.

b Assuming a spin temperature of 100 K.

c Assuming a spin temperature of 6000 K.

by 370 ± 10 km s$^{-1}$ and for CE is blueshifted by 700 ± 10 km s$^{-1}$ from the systemic velocity of the source (16,558 ± 3 km s$^{-1}$). No absorption was found at either C1 or C2 (see Figure 2). We calculate a limit on the HI opacity at the location of C1 and C2, and obtain less than 0.17 and less than 0.03, respectively. Figure 3 shows a map of both the central velocity and width of the HI absorption profiles over the source. Figure 4 shows a velocity slice of the continuum-subtracted cube (right panel), accompanied by the HI opacity distribution over the source (left panel). This result shows that either the two HI abs. in binary SMBH 0402+379
Rodriguez+2009, Morganti+2009

HI emission

and absorption

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variability/transients

quasi-periodic accretion, light curves
summary plot

- inspiral/mergers via transients?
- direct imaging
- radio-jet morphology
- pulsar timing arrays

Milky Way SMBH Schwartzchild radius

Projected separation / parsec vs. redshift

SKA1-mid
SKA2-mid
1. multiple SMBH science will become mainstream with next-generation facilities

2. the SKA is likely to lead through broad range of techniques and perspectives
summary

• most modes of the SKA will probe cosmic SMBH evolution history
• will do so over > 6 dex of orbital separation dynamic range
• high complimentarily between imaging & non-imaging methods which must form a consistent, cohesive picture
• SKA could lead the way ahead of other large multi-wavelength facilities
• gravitational wave astronomy will provide deep insights on galaxy evolution