VaDAR: Varstrometry for Dual AGN using Radio interferometry

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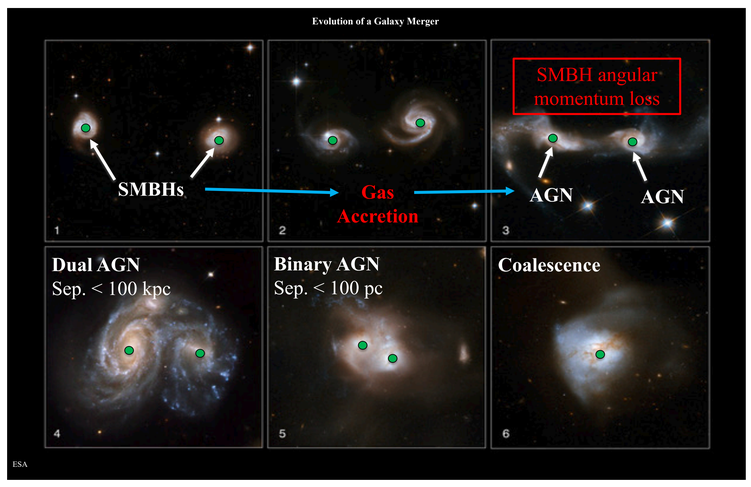
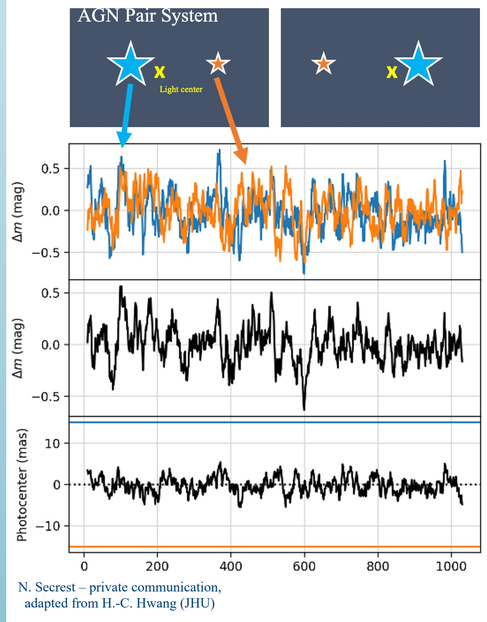
Introduction: AGN Pairs

- Galaxy mergers can result in pairs of gravitationally-bound supermassive black holes (SMBH; Kormendy & Richstone+95)
- Gas is driven towards nuclei, accretes onto SMBH, and ignites as active galactic nuclei (AGN; Hopkins+08)
- Confirmed AGN pairs are rare (< 50); most are found at local redshifts and higher separations (Pfeifle+in press.)
- High resolution observations are generally necessary for confirmation, but require some method of pre-selection
- Of particular interest are systems at “cosmic noon” (1 < z < 3), but an observational gap exists where separations are greater than 6 kpc at redshifts greater than 1 (Richards+06)



The Varstrometry Method

- *Gaia*’s milliarcsecond astrometric accuracy has facilitated the identification of astrometrically-variable quasars that may be associated with AGN pairs (Shen+21, Chen+22)
- Drivers of Astrometric Variability:
  - Jet activity
  - Obscured AGN
  - Stellar activity in host galaxy
  - Lensed quasars
  - Wandering stellar-mass black holes
  - AGN pair systems



N. Secrest – private communication, adapted from H.-C. Hwang (JHU)

For an AGN pair, unresolvable with *Gaia*, the photocenter appears to shift on the sky as the AGN vary stochastically (Sesar+11)

If the component AGN were resolvable with *Gaia*, we might observe an individual light curve for both

Instead, since *Gaia* is resolution-limited (~ 0.2”, Fabricius+21), a joint-variability light curve is observed

The shifting of the photocenter on the sky manifests itself in the photometric data as excess “jitter”

Variability + astrometry = **varstrometry!** **Hwang et al. 2019**

Can varstrometry, in combination with high-resolution radio interferometry (VaDAR), select AGN pair system associated with radio-loud quasars?

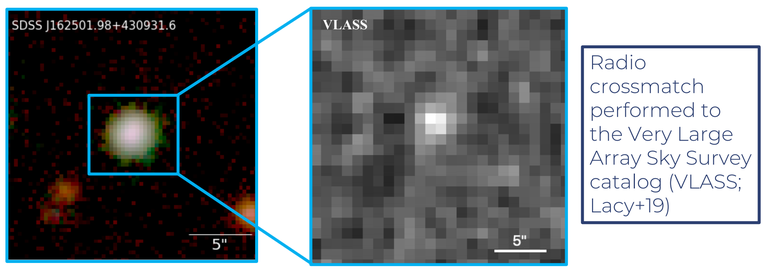
VaDAR Sample + Observations

- Sample:
  - 18 quasars (SDSS DR16Q, *Gaia* DR3 to within 1.5”)
  - z > 0.5, *Gaia* G mag < 20
  - *Astrometric_excess_noise_significance (AENS)* > 5

Astrometric excess noise (AEN): amount of statistical dispersion required such that *Gaia*’s astrometric solution for the source leaves no unexplained variance.

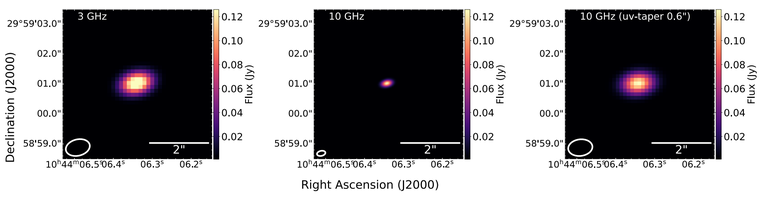
  - Radio match with the Very Large Array Sky Survey (VLASS; Lacy+19), a 3 GHz continuum survey = 18 quasars

- Observations:
  - VLA – A configuration
  - S-band (2-4 GHz, 0.65”)
  - X-band (8-12 GHz, 0.2”)



Radio crossmatch performed to the Very Large Array Sky Survey catalog (VLASS; Lacy+19)

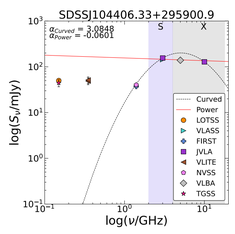
New Radio Results

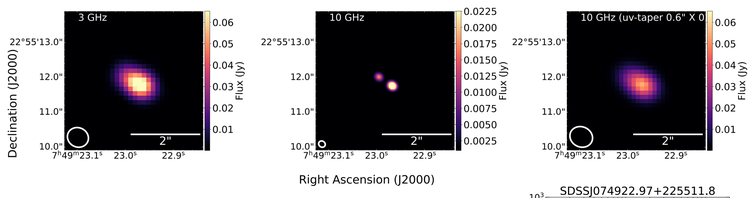


Left: VLA 3 GHz observations. Middle: VLA 10 GHz observations. Right: VLA 10 GHz uv-tapered observations. Beams shown in bottom left.

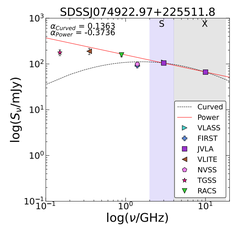
104406.33+295900.9:
- Unresolved, bright radio source
- Existing VLBA observations (5 GHz; Helmboldt+07) show similarly **unresolved** source at sub-milliarcsecond scales

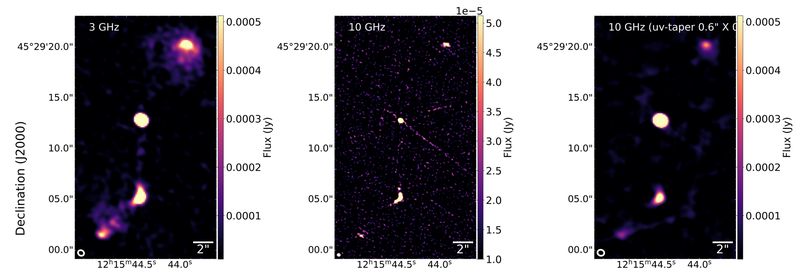
Broadband radio SED showing the new, quasi-simultaneous VLA observations in purple squares, and additional existing archival measurements. The SED has been modeled with both a standard power law (red line) and a curved power law (dashed black line), following Patil+22. Resultant spectral indices are listed.



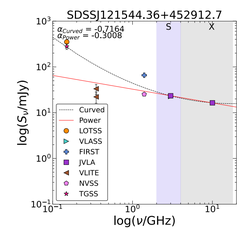


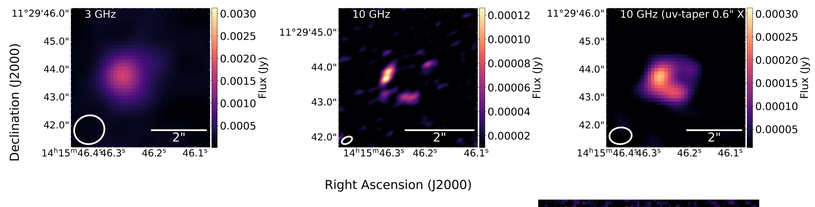
074922.97+225511.8
- Unresolved, extended radio source at 3 GHz, resolves into two clear peaks at 10 GHz
- **Dual AGN candidate** with a separation of 0.46” (3.84 kpc)
- Confirmed with HST (Shen+21)



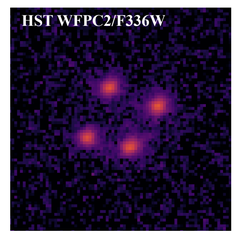


121544.36+452912.7:
- Canonical **radio** jet: core is compact and flat, lobes are diffuse and steeper
- Jets are the likely driver of the astrometric variability, though core could be hiding more compact structure



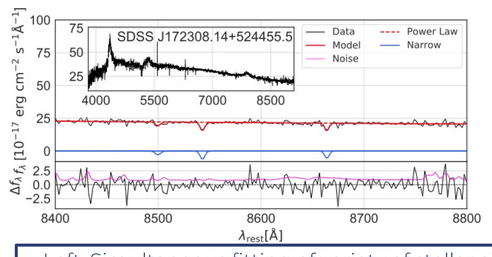


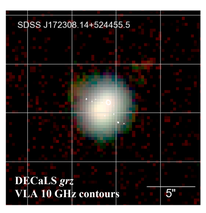
141546.24+112943.4:
- Unresolved, extended radio source at 3 GHz, resolves into multiple peaks at 10 GHz
- HST observations reveal a **lensed quasar**, an Einstein Cross known as the Cloverleaf System (Chartas+04)



Contaminants

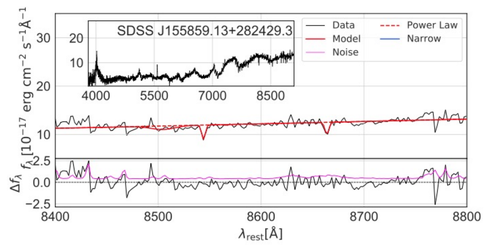
172308.14+524455.5: Star+quasar superposition (CaT, NaD, Hα)

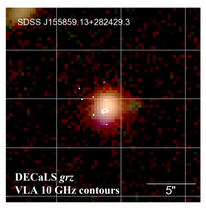




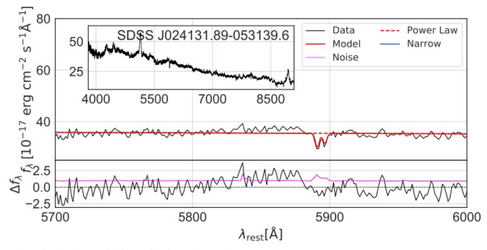
Left: Simultaneous fitting of variety of stellar absorption lines with BADASS (Sexton+2021), with full SDSS spectrum insert. Right: Dark Energy Camera Legacy Survey (DECaLS; Dey+19) tri-color images, with 10 GHz VLA radio contours overlaid in white.

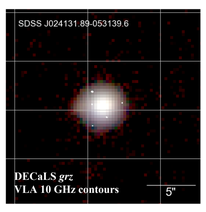
155859.13+282429.3: Star+quasar superposition (CaT, NaD)



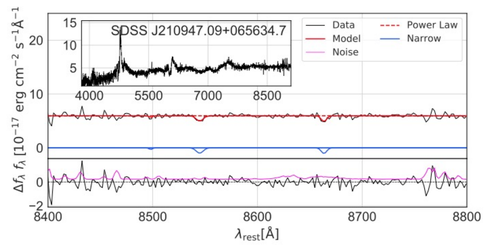


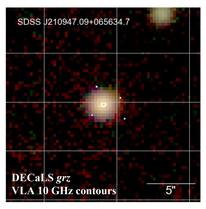
024131.89-053139.6: Star+quasar superposition (NaD)



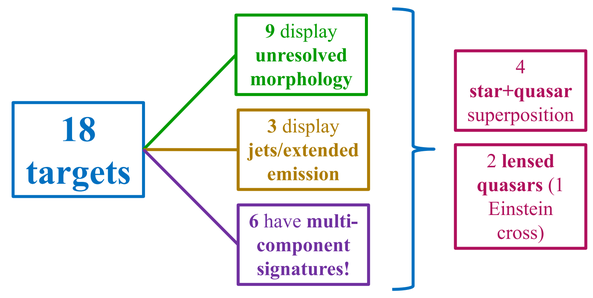


210947.09+065634.7: Star+quasar superposition (NaD, CaT)

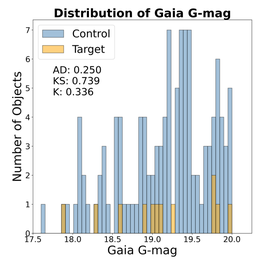




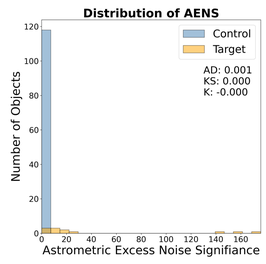
The Overall Sample



- Overall Sample:
  - Target sample compared to matched control sample
    - Targets: 12 objects with **AENS > 5**, G mag < 20, z > 0.5
    - Controls: 120 objects with **AENS < 4**, G mag < 20, z > 0.5
      - i.e., no significant astrometric variability

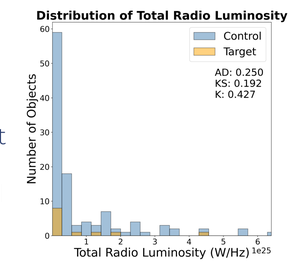


Samples **are** comparable for controlled parameters such as G mag and redshift.



Samples **are not** comparable for AENS, as controls should not display significant astrometric variability.

Comparison of total radio luminosity indicates that the targets are comparable to the controls. This indicates that the targets are not radio-loud, when compared to the controls, likely eliminating radio-loud blazars as a potential driver of AENS.



Histograms show comparison of target to control samples. P-values from Anderson-Darling, Kolmogorov-Smirnov, and Kuiper tests are shown (Schwartzman+submitted).

Key Results

- What sample does the radio+varstrometry (VaDAR) method select for?
  - Diverse morphology (lenses, pairs, jets, etc.)
  - ~40% dual AGN/lensed quasar systems
  - ~25% star+quasar superposition
- Can varstrometry, in combination with high-resolution radio interferometry, selected AGN pair systems associated with radio-loud quasars?
  - Yes, this pilot study has identified previously unknown candidate AGN pair systems.
  - Further follow-up is necessary to fully understand the unresolved radio targets (Schwartzman+submitted)

Future Studies

- Very Long Baseline Array (VLBA)
  - 7 targets observed at S- and X-band
  - Higher resolution, sub-milliarcsecond morphology
  - Probing smaller scale structure in unresolved targets
  - Calibration ongoing, look for results this fall!

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