Inspiralling Supermassive Black Holes as Tracers of Galaxy Mergers

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We Expect Inspiralling SMBHs in Merger-Remnant Galaxies

Models and simulations of inspiralling SMBHs in merger-remnant galaxies successfully reproduce:

- $M_{BH} - \sigma$ relation (e.g., Wyithe & Loeb 2003)
- Observed luminosity function of quasars (e.g., Volonteri et al. 2003)
- Quasar population evolution with $z$ (e.g., Kauffmann & Haehnelt 2000)
- Many other galaxy/quasar scalings (e.g., Hopkins et al. 2008)
Yet Very Few Dual SMBHs in Galaxies Have Been Found

We can identify SMBH pairs observationally if they power AGN

Mrk 463
$z = 0.05$
$\Delta x = 4$ kpc
Bianchi et al. 2008

NGC 6240
$z = 0.02$
$\Delta x = 0.7$ kpc
Komossa et al. 2003

0402+379
$z = 0.06$
$\Delta x = 7$ pc
Rodriguez et al. 2006
Our Goal: To Build a Statistical Sample of Inspiralling SMBHs

Two purposes:

1. Explore the kinematics of SMBH mergers, which are expected to produce gravity waves

Previously, inspiralling SMBH pairs identified with X-ray/radio/IR resolution of two separate SMBHs

Need for spatial resolution limits these techniques to nearby galaxies (examples are at $0.02 < z < 0.06$)
New Technique for Identifying Inspiralling SMBHs

We identify inspiralling SMBH pairs in galaxies using optical spectroscopy.

Can find inspiralling SMBHs at high redshifts, no need to spatially resolve close pairs.

Enables a systematic search for inspiralling SMBHs rather than serendipitous discoveries.
Our Goal: To Build a Statistical Sample of Inspiralling SMBHs

Two purposes:

2. Independently determine the galaxy merger rate

Usually, galaxy merger rate estimated in one of two ways:

Counts of close dynamical pairs of galaxies  
Counts of galaxies with disturbed morphologies

NASA  
ACS/NASA
New Technique for Identifying Galaxy Mergers

Simulations suggest close pairs may not be good proxies for mergers (e.g., Wetzel et al. 2008)

Galaxy morphologies often misclassify mergers (e.g., De Propris et al. 2007)

Instead, identify galaxy mergers from spectroscopic signatures of their inspiralling SMBHs
Typical AGN Spectrum

AGN is at rest with respect to the host galaxy
Dual AGN

Red galaxy at $z = 0.71$

Double-peaked $[O \ III]$ emission lines separated by 630 km/s

Galaxy hosts a dual AGN: Two AGN inspiralling within the host galaxy

Gerke et al. 2007
Offset AGN:
One set of AGN emission lines offset in velocity from the galaxy’s stars
Implies that galaxy may host an AGN and a quiescent SMBH
Systematic Search for Dual and Offset AGN in DEEP2

DEEP2 Galaxy Redshift Survey
Collaboration between UC Berkeley and UC Santa Cruz (PIs Marc Davis and Sandy Faber)
DEIMOS spectrograph on Keck II
80 Keck nights over 3 years
Covered 3 deg$^2$ over 4 fields
Spectra for 50,000 galaxies out to $z=1.4$
Sample Selection: AGN in Red Galaxies

Select AGN by:

1. $[\text{O III}] \lambda 5007/\text{H}\beta > 3$

2. Color cut to select red galaxies
   $U-B > -0.032(M_B+21.62)-1.035$ (Willmer et al. 2006)

91 AGN in red galaxies
$0.34 < z < 0.82$
Offset and Dual AGN Found by a Discrepancy between Absorption and Emission Redshifts

Mask out emission lines and fit an early-type galaxy template spectrum $\rightarrow$ measure $z_{\text{abs}}$

Fit Gaussian to a window around the peak of the [O III] emission line $\rightarrow$ measure $z_{\text{em}}$
Velocity Distribution of AGN

Eliminate objects with $<3\sigma$ velocity difference:

Comerford et al. 2009a
Found 32 Dual or Offset AGN

Result: 2 dual AGN and 30 offset AGN

Comerford et al. 2009a
Offset and Dual AGN Are Uniformly Distributed in the AGN Population
\[ \text{[O III] } \lambda 5007 \text{ Emission from One AGN} \]
2 Dual AGN

$z = 0.71$
$\Delta v = 630 \text{ km/s}$
$\Delta x = 1.2 \text{ kpc}$

$z = 0.62$
$\Delta v = 440 \text{ km/s}$
$\Delta x = 2.3 \text{ kpc}$
30 Offset AGN

$\Delta v = v_{\text{em}} - v_{\text{abs}}$

Comerford et al. 2009a

$\Delta v = -140 \text{ km/s}$

$\Delta v = -120 \text{ km/s}$

$\Delta v = -94 \text{ km/s}$

$\Delta v = 90 \text{ km/s}$

$\Delta v = 110 \text{ km/s}$

$\Delta v = 170 \text{ km/s}$
What Causes the Velocity Offsets?
Outflows Cause Stratified Velocity Structure...

Strong, decelerating outflow in inner NLR of AGN can cause velocity offsets of [O III] emission lines (e.g., Zamanov et al. 2002; Komossa et al. 2008)

Outflow would impart:

> Higher velocity to nearby high ionization lines such as [O III]

> Lower velocity to low ionization lines, such as [O II] and Hβ, that are generated further from the AGN

NASA/CXC/M. Weiss
…But No Stratification Seen in Velocity Structure of Our AGN

In a spectrum of an offset or dual AGN, [O II] and Hβ emission lines are at the same velocity as [O III] emission lines.

The velocity shifts we measure are consistent with bulk motion of the AGN within the host galaxy rather than outflows.
Outflows in Nearby Seyferts

Outflows in NGC 1068 and NGC 4151 show [O III] blueshifts and redshifts of several hundred km/s (Das et al. 2005, 2006)

Outside ~100 pc, the outflow velocity drops to zero

[O III] intensity of NLR in NGC 4151:

Das et al. 2005
Such Outflows Would Not Cause a Net [O III] Offset in DEEP2

A DEIMOS pixel subtends 1 kpc at $z \sim 0.7$

Kinematics on sub-kpc scales would not be resolved with DEEP2

Rather, co-adding STIS spectra of NGC 1068 yields a broadened [O III] emission line with no overall offset in velocity
Dust and Outflows Combined Could Produc[e] [O III] Velocity Offsets

Pathologically patchy dust could obscure only the blueward (redward) portion of the outflow.

But:
Such configurations of dust are not seen locally.

Our sample is red galaxies, which shouldn’t have much dust.

Outflows would expel dust from center.

Outflowing galaxies exhibit larger [O III] velocity dispersions than [O III] velocity offsets, which is not the case for our sample.
Do Inspiralling SMBHs in Galaxy Mergers Produce the Velocity Offsets?

Expect to see velocity-offset AGN emission lines caused by inspiralling SMBHs in merger-remnant galaxies.

Our velocity offsets are consistent with expectations from mergers:

> Symmetric velocity distribution
> Consistent [O II], Hβ, and [O III] velocities indicate bulk motion of AGN
> AGN exhibit ~1 kpc spatial separations
Offset and Dual AGN Are the Products of Galaxy Mergers

Most plausible explanation for offset [O III] lines in our sample: AGN inspiralling within the host galaxy

Our sample likely consists of merger-remnant galaxies hosting dual SMBHs, where one or both power AGN

Dual AGN:

Offset AGN:

Komossa et al. 2003

Barth et al. 2008
Half of AGN Host Galaxies Are Merger Remnants

After adding an interpolated number of low velocity separation objects, we expect there to be 40-55 offset or dual AGN in our sample.

Of the 91 red galaxies hosting AGN, roughly half are moving within the host galaxy due to a recent merger.
We Find a Strong Link between AGN Activity and Galaxy Mergers

That half of red galaxies hosting AGN are also merger remnants signals a strong connection between AGN and galaxy mergers.

Mergers between late-type galaxies can trigger nuclear gas inflows that power AGN -- may also be true for red galaxies.

Springel et al. 2005
32 dual and offset AGN we find suggests a lower limit that > 2% of red galaxies 0.34 < z < 0.82 are undergoing mergers

Convert our 40 – 55 expected dual or offset AGN to a merger fraction of

\~30\% \left( \frac{10\%}{f_{\text{lum}}} \right) \text{ for red galaxies } 0.34 < z < 0.82

or a merger rate of

\~3 \text{ mergers/Gyr} \left( \frac{100 \text{ Myr}}{t_{\text{combine}}} \right) \left( \frac{10\%}{f_{\text{lum}}} \right) \text{ for red galaxies } 0.34 < z < 0.82
Other Ways to Identify Dual AGN

> Select candidates by optical imaging, follow up with spectroscopy to confirm
COSMOS galaxy at $z=0.36$ with two bright nuclei separated by 2.5 kpc.

X-ray (XMM-Newton), infrared (Spitzer IRAC), and radio (VLA) detections all show the galaxy has AGN activity.

But are both nuclei AGN? 

Comerford et al. 2009b
Spectroscopic Confirmation of COSMOS Dual AGN

DEIMOS spectrum shows both nuclei are AGN

Dual AGN with velocity separation 150 km/s and spatial separation 2.5 kpc
2D DEIMOS Spectrum of COSMOS Dual AGN
Dual/Offset AGN Are Observational Probes of Galaxy Mergers

> First systematic survey of inspiralling SMBHs: we find 2 dual AGN and 30 offset AGN in DEEP2 red galaxies

> Powerful new way of identifying dual SMBHs and galaxy mergers

> Half of red galaxies hosting AGN are also merger remnants, signaling a strong link between AGN activity and galaxy mergers

> Merger fraction ~30%, merger rate ~3 mergers/Gyr for red galaxies 0.34 < z < 0.82
Towards Building a Statistical Sample of Inspiralling SMBHs

> Found 32 dual and offset AGN in DEEP2 spectra

> Dual AGN candidates can be identified in HST imaging and confirmed with optical spectroscopy

> Slit spectroscopy may help identify which objects with double-peaked AGN emission lines are dual AGN