Measuring black-hole masses and the evolution of the $M_{bh}:M_{bulge}$ relation

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The evolution of the $M_{bh}:M_{bulge}$ relation

Outline

- The $M_{bh}:M_{bulge}$ relation: local galaxies
- The AGN perspective: estimating $M_{bh}$ and possible problems
- Evolution of $M_{bh}:M_{bulge}$ relation $0<z<4$
- Conclusions
- What can we do in the future
The evolution of the $M_{\text{bh}}:M_{\text{bulge}}$ relation

Now well established fact, at least for massive galaxies, that the central black-hole mass is tightly correlated with galaxy spheroid/bulge mass.

What’s the historical background to this?
The evolution of the $M_{\text{bh}}:M_{\text{bulge}}$ relation

Historical perspective: Local galaxies

Famous paper by Kormendy & Richstone (1995) first to show from observations that black-hole mass and bulge luminosity were correlated.
The evolution of the $M_{bh}:M_{bulge}$ relation

**Historical perspective: Local galaxies**

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Prompted by refurbishment of HST allowing gas dynamics to studied within black-hole sphere of influence:
The evolution of the $M_{bh}:M_{bulge}$ relation

Historical perspective: Local galaxies

Step forward to 1998 and second famous paper from Magorrian et al. (1998)

Dynamical modelling of stellar populations of nearby massive galaxies suggested correlation between bulge mass and mass of central “massive dark object”

The $M_{bh}:M_{bulge}$ now often referred to simply as “the Magorrian relation”
The evolution of the $M_{bh}:M_{bulge}$ relation

Historical perspective: Local galaxies

The so-called $M_{BH}-\sigma$ relation: $M_{BH} \propto \sigma^{3.75\pm0.3}$

Gebhardt et al. (2000)
The evolution of the $M_{\text{bh}}:M_{\text{bulge}}$ relation

Both correlations have very low associated scatter

*Independent* of galaxy morphology

$M_{\text{BH}} \sim 0.002 M_{\text{SPH}}$
The evolution of the $M_{bh}:M_{bulge}$ relation

The black-hole: spheroid relation

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Why is this important?

Black hole and galaxy evolution intimately related

All massive galaxies pass through active AGN phase
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The black-hole: spheroid relation

Why is this important?

Black hole and galaxy evolution intimately related

All massive galaxies pass through active AGN phase

Clearly some form of feedback relation: black holes regulating star formation

AGN “feedback” now important ingredient of galaxy formation models
How do you study $M_{BH} : M_{SPH}$ evolution?

Active galaxies (AGN) offer the only opportunity for progress
Can estimate both black-hole and galaxy mass
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- Assume BLR is virialised
- Velocity from broad-line widths
- Radius from R-L correlation (e.g. Kaspi et al. 2000)
- $0 < z < 0.8$ H$\beta$ line-widths
- $0.8 < z < 2.0$ MgII line-widths (McLure & Jarvis 2002)
- $z > 2$ CIV line-widths (Vestergaard 2002)
Not all hunkydory with any virial estimator though…

Doppler boosting can disguise real radio power

Jarvis & McLure 2002
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Doppler boosting can disguise real radio power and it has been known for many years that there is a correlation between broad emission-line width and the core-to-lobe ratio of radio-loud source (Wills & Browne 1986; Brotherton 1996; Rokaki et al. 2003)

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Galaxies provide spheroid mass

$$\frac{M_{BH}}{M_{SPH}} (z)$$
Do AGN follow the $M_{bh}:M_{bulge}$ relation?

Low-redshift quasars/Seyferts follow standard $M_{bh}-L_{bulge}$ correlation (McLure & Dunlop 2002)

Low-redshift Seyferts follow standard $M_{bh}-\sigma$ correlation (Nelson et al. 2004)

AGN appear to be unbiased tracer of $M_{bh}:M_{bulge}$ relation
Recent studies: Seyfert galaxies

Woo et al. (2008), Treu et al. (2007)
latest results of on-going study of $M_{bh}$-$\sigma$ and $M_{bh}$-L$_{bulge}$ relations using sample of broad-line Seyferts at z\sim 0, z\sim 0.4 and z\sim 0.6

AGN broad lines provide black-hole masses
SDSS+Keck spectra provide velocity dispersions
ACS imaging provide bulge luminosities at z\sim 0.4

HST ACS i-band imaging
Recent studies: Seyfert galaxies

Results of study of $M_{bh}-\sigma$ and $M_{bh}-L_{bulge}$ relations at $z\sim0.4$:

Claim is that results are inconsistent with no evolution at 95% CL
Recent studies: Seyfert galaxies

Latest results from Woo et al. (2008)

- Addition of comparison sample of Seyferts at $z=0$ drawn from the SDSS
- Small sample (5 objects) added at $z=0.57$
- $z=0$ Seyferts sit on standard $M_{bh}$-σ relation
- $z>0.3$ samples are off-set

Dashed line is evolution of the form:  
$$\Delta M_{BH} \propto (1+z)^{3.1 \pm 1.5}$$
Recent studies: Quasars

Peng et al. (2006)
Doing things the hard way

Study of the evolution of the $M_{\text{bh}}$-$L_{\text{bulge}}$ relation using literature sample of quasars with HST imaging at $1<z<3$

Plus, modelling of host galaxies in lensed quasar systems......

- 31 objects from the CASTLES survey
- 15 objects from the literature

Example modelling of one CASTLES quasar
Recent studies: Quasars

Peng et al. (2006)

- Conclude that black-holes are a factor 5-6 more massive at z~2
- Quasar hosts cannot be fully assembled at these redshifts
Recent studies: Radio-loud AGN

McLure, Jarvis et al. (2006)
Doing things the quick and dirty way...

• 3CRR sample of radio-loud AGN

• Rely on radio-loud unification: Radio galaxies and radio-loud quasars drawn from same underlying population

• Bulge masses from radio galaxies

• Black-hole masses from quasars

○ No apparent evolution of bulge masses: RGs fully assembled?
○ Black-hole masses increase with redshift
Recent studies: Radio-loud AGN

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Doing things the quick and dirty way...

- 3CRR sample of radio-loud AGN
- Rely on radio-loud unification: Radio galaxies and radio-loud quasars drawn from same underlying population
- Bulge masses from radio galaxies
- Black-hole masses from quasars

Solid line is evolution of the form: $\Delta M_{BH} \propto (1+z)^{2.1\pm0.7}$

Within the uncertainties, good agreement with Woo et al. (2008) and Peng et al. (2006)
Conclusions

- Redshift evolution of $M_{\text{bh}}:M_{\text{bulge}}$ relation key constraint on galaxy evolution models
- AGN provide the only practical method for tracing evolution
- Tests suggest that AGN are unbiased tracers at low redshift
- Various studies of luminous AGN suggest $M_{\text{bh}}:M_{\text{bulge}}$ ratio evolves with redshift (although this does not appear to be true for Sub-mm galaxies)
- At present evolution appears to be: $\Delta M_{\text{BH}} \propto (1+z)^{2\pm1}$

Uncertainties and potential sources of bias are still large/unknown; Evolution (if it exists) only demonstrated at $\sim 2\sigma$ level.
Recent studies: Sub-mm galaxies

Alexander et al. (2008)

Sub-mm galaxies at z~2 appear to lie factor of 3-5 below local relation
Evolution of the $M_{\text{bh}}-\sigma$ relation: the future

TOOT1630+4530

Noise Spectrum

Herbert, Jarvis, Willott, McLure in prep.
Evolution of the $M_{bh}$- $\sigma$ relation: the future

Jarvis, McLure & Swinbank in prep.
EUCLID (2017)

- Merger of SPACE and DUNE for the ESA Cosmic Visions Programme
- Satellite able to carry out both imaging and spectroscopy over 20000 sq.deg
- (RIZ)+YJH filters for imaging at 0.2 arcsec resolution
- Near-IR spectroscopy of 1/5 of all sources in 20000 sq.deg to $H_{AB}=23$
- Deep survey of 10 sq.deg with spectroscopy of ~2 million galaxies to $AB=26$

Design study bid to STFC last month. Currently exploring links between the spectroscopic science and with SKA.