Tracing the Growth of Black Holes in the Distant Universe

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Ultra-deep X-ray surveys: Chandra deep fields

4Ms CDF-S field; Xue et al. (2011)

2Ms CDF-N field: Alexander et al. (2003)

Best observed regions of the sky over ~0.1 sq deg at X-ray, optical, infrared, submillimetre, and radio wavelengths
Talk Overview

Introduction

Typical growth of distant black holes

Evidence for large-scale outflows?

Searches for hidden heavily obscured black holes
Massive black holes are ubiquitous

Central black hole in our Galaxy
Black holes grow through mass accretion

Termed Active Galactic Nuclei (AGN)

Moderate luminosity: Seyfert galaxy

\[ \Delta E \propto \Delta mc^2 \]

Significant emitters over (at least) X-ray-radio wavelengths

Very high luminosity: quasar
Global Importance of AGN activity

Tremaine et al. (2002)

$M_{bh}/M_{sph} \sim 10^{-3}$

Action: Gas accretion/Star formation

$K_s(K_b) - \text{dispersion (km s}^{-1}\text{)}$
Global Importance of AGN activity

- Presence of a massive stellar bulge implies the presence of a massive black hole
- Implies all massive galaxies must have hosted AGN activity at some time
- Tightness of the relationship suggests regulated growth despite a factor $\sim 10^9$ difference in size scale!
Large-scale influence of AGN activity?

AGN outflows often argued to be responsible for:
- rapid shut down of SF
- forging black-hole-galaxy relationship
- metal enrichment of IGM

Clear observational evidence of influence in galaxy clusters: what about in individual galaxies?

Early work: Silk & Rees (1998); Fabian (1999)
How quickly are black holes growing today?

Grew more rapidly in past
Growing more rapidly now

Volume average growth

Heckman et al. (2004)
See Greene et al. (2005), Goulding et al. (2010) and others for lower-mass constraints
How quickly are black holes growing today?

Growing more rapidly now
Grew more rapidly in past

Volume average growth

Smallest BHs growing fastest

Heckman et al. (2004)

See Greene et al. (2005), Goulding et al. (2010) and others for lower-mass constraints

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This implies that most of the action occurred in the distant Universe: we need to identify and study distant AGNs.
Can we find these AGNs? The challenge of obscuration

Risaliti et al. (1999)

![Bar chart showing number of objects for different categories.]

X-ray absorption

Rest 0.8-24 keV (z~0.5-2 X-ray energies)

Vignati et al. (1999)
Can we find these AGNs? The challenge of obscuration

Majority of AGNs are obscured and perhaps half are Compton thick, where a large fraction of the emission is probably not direct (scattering and reflection).

Risaliti et al. (1999)

X-ray absorption

Rest 0.8-24 keV (z~0.5-2 X-ray energies)

Vignati et al. (1999)
Can we find these AGNs? The challenge of star formation in the host galaxy

Dusty Starburst

Probe these regions using infrared

Central engine
Obscuration
Can we find these AGNs? The challenge of star formation in the host galaxy

Star formation in the host galaxy can extinguish or dilute the AGN signatures

Probe these regions using infrared
The Typical Growth of Distant Black Holes
X-ray Surveys: Penetrating Probe of AGN activity

Murray et al. (2005)
5 ks Bootes

2-4 Ms CDF-N & CDF-S
Alexander et al. (2003);
Luo et al. (2008); Xue et al. (2011)

Penetrate large gas columns

Brandt & Hasinger (2005)
Complemented by extensive and deep multi-wavelength coverage

Some key facilities: Now

- Spitzer: mid-IR
- Herschel: far-IR
- JCMT-SCUBA2: submm
- HST: optical-near-IR

Some key facilities: near future

- ALMA: submm/mm
- NuSTAR
- First focusing 6-78 keV telescope
- VLT-KMOS

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Basic Properties of the X-ray AGNs

Most X-ray AGNs are at z<1: some spectroscopic bias

X-ray surveys have identified largest unambiguous AGN source density to date (~10,000 deg$^2$; Bauer et al. 2004, Xue et al. 2011): ~30-50% lack spec-zs but have phot-zs

Barger et al. (2003); Szokoly et al. (2004); Tozzi et al. (2006) amongst others
Broad variety of sources are found

Brandt et al. (2001)

Optically "dull" AGNs
Barger et al. (2002)

Optically normal AGNs
Barger et al. (2002)
Optical-near-IR emission typically dominated by host

The optical-near-IR emission from most X-ray AGNs dominated by the host galaxy - not great for estimating AGN luminosities but good for determining host-galaxy properties.
Host galaxies are typically luminous ($\sim L^*$) and massive ($>3 \times 10^{10}$ solar masses)

Host galaxies lie in same region of colour-magnitude diagram as typical massive galaxies

Clustering (and dark-matter halos) also consistent with those of massive galaxies ($\sim 10^{12}$-$10^{13}$ solar masses; Hickox et al. 2009)

Brusa et al. (2009)

Colour magnitude diagram

Xue et al. (2010)
Most AGNs host not clearly in major mergers - like typical massive galaxies

Only ~15% are in major mergers (lower limit to true fraction)

See also Grogin et al. (2005), Pierce et al. (2007), Georgakakis et al. (2009), Kocevski et al. (in prep), Schawinski et al. (2011)

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The global increase in specific star-formation rates (stellar mass/star formation rate) tracks that seen in the host-galaxy population. Driven by available cold-gas supply? 

GOODS Herschel: Mullaney et al. (in prep)

See also Lutz et al. (2010), Mullaney, DMA et al. (2010); Shao et al. (2010)

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AGN fraction: BH growth duty cycle

But environment also plays a role - AGN fraction larger in dense regions: a factor ~6x higher in z~3.09 SSA22 protocluster than in field (Lehmer, DMA et al. 2009); see also Digby-North et al. (2010)

AGN fraction rises with host-galaxy mass: characteristic AGN fraction of ~10% (black hole is growing for ~10% of the time; see also Bundy et al. 2008)

Xue et al. (2010)
Modest black-hole growth rates at $z<1-1.5$

- Growing more rapidly now
- Grew more rapidly in past

See also Ballo et al. (2007); Alonso-Herrero et al. (2008)

Typical growth times are long. But these distant massive black holes ($>10^8$ solar masses) are growing more rapidly than those seen locally - evidence for black-hole downsizing
Our global picture of typical distant black-hole growth is that black holes in massive galaxies are growing ~10% of the time at comparatively modest rates

No clear increase in star formation due to the presence of AGN activity
Conundrum: increasing $L_{\text{IR}}/L_X$ with redshift

Taken at face value the increase in $L_{\text{IR}}/L_X$ suggests the galaxy grew more rapidly than the black hole in the past: but significant caveats:

- Bulge star formation? Changing AGN fraction (BH duty cycle)? Missing AGNs? Changing IMF? Or are moderate AGNs not important for BH-spheroid mass relationship?

Increase in $L_{\text{IR}}/L_X$ with redshift implies more star formation without more AGN activity?

Mullaney et al. (in prep)

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Evidence for large-scale energetic outflows?
Rapid growth phase

Di Matteo et al. (2005)

The Sanders/Hopkins et al. evolutionary picture

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The Sanders/Hopkins et al. evolutionary picture

Di Matteo et al. (2005)

Rapid growth phase

ULIRGs/SMGs

Quasars

T = 160 Myr
z~2 ULIRGs/SMGs: rapid black-hole “burst” phases?

High-Eddington ratios: rapid BH growth

Submillimetre galaxies are good candidates for this phase:

Merger driven z~2 activity (e.g., Tacconi et al. 2006)

Evidence that they will evolve into an optically bright quasars (e.g., Page et al. 2004; Alexander et al. 2008)

Rapid galaxy and black-hole growth: runaway growth unless regulated?

The Sanders/Hopkins et al. evolutionary picture
Spatially resolved spectroscopy: large-scale outflows?

z~2 ULIRG: star formation being halted by galaxy wide outflow traced by broad [OIII]?  

Alexander et al. (2010)

Not yet clear how common: need more IFU observations to determine how ubiquitous - KMOS on VLT?

See also Nesvadba et al. (2006, 2007, 2008) for radio-loud AGNs

C. Harrison, DMA, Swinbank et al. (in prep)
Have the X-ray surveys missed any heavily obscured distant AGNs?
Yes they certainly have: even luminous systems have been missed

The missing heavily obscured AGNs may represent an important (early) black-hole growth phase (e.g., Fabian 1999; Hopkins et al. 2006): finding them could be more than just a bookkeeping exercise.

Evidence: stacked X-ray data of X-ray undetected candidate AGNs in narrow bands

Daddi et al. (2007); Fiore et al. (2008, 2009); Treister et al. (2008); See also Worsley et al. (2005)
Deeper X-ray data reveals even more convincing AGN signatures

Composite X-ray spectrum of the heavily obscured AGN sub population

Strong reflection dominated AGNs - possible strong Fe K line directly revealing Compton-thick AGNs

HST morphologies look no different to typical z~2 AGNs

See also Alexander et al. (2008), Feruglio et al. (2011), and Georgakakis et al. (2010; for z~1 systems)
But we have only scraped the surface: need full SED modeling

z=2 spectral energy distribution

Herschel key project in GOODS fields: 100+160um (250+350+500um)

Herschel+Spitzer: infrared SEDs (3-500um) to identify AGN and star formation

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Development of empirical AGN-starburst templates

Carefully constructed AGN and star-forming galaxy templates: tested against AGNs and galaxies in the local Universe - AGN is consistent with clumpy torus

Mullaney, DMA et al. (2011)
Application of SED fitting: finding radio-excess AGNs

Variety of radio-excess AGNs

Del Moro, DMA et al. (in prep)

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How many AGNs are we missing at X-ray energies?

Best-fitting AGN luminosity at rest-frame 6μm

Some fraction of the luminous AGNs missed in X-rays (~25-50%)

Many are clearly very heavily obscured

Now need to better characterise their space density, host galaxy properties etc.

Del Moro, DMA et al. (in prep)
• **When and where did distant black holes grow?**
  
  Majority appears to have occurred in massive galaxies - the host galaxies of AGNs and non AGNs appear very similar.

  The X-ray surveys generally identify massive (>10^8 solar mass) black holes, which are growing with a ~10% duty cycle. Growth rates are modest but more rapid than similar mass BHs locally: evidence for downsizing

  More star formation per unit AGN activity at higher redshift than seen today: a conundrum?

• **Do we see evidence for large-scale outflows (as predicted by some models)?**

  Using IFU data - spatially resolved spectroscopy - we certainly appear to see outflows in some rapidly growing systems. Not clear how common - need VLT-KMOS and better statistics to know

• **How many AGNs are missed in the X-ray surveys?**

  Ongoing work but appears to be ~25-50% of the luminous AGNs. A population of heavily obscured (reflection dominated) AGNs has been found, many of which may be Compton thick. Host galaxies look similar to typical distant AGNs.