Synergy between deep X-ray and infrared surveys: AGN and star formation activity

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Two key issues in observational cosmology

Census of AGNs/black-hole growth

AGN-star formation connection

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

Action: AGN activity

Action: Star formation
Obscured Growth of Galaxies and Black Holes

Primary source (X-ray-optical)

AGN, star formation

Heats the dust

Dust

Reprocessed emission (infrared/submm)

Observe thermal spectrum in ~3-300um band
X-ray Surveys: Penetrating Probe of AGN activity

Detection of even low-luminosity AGN out to high redshift

Murray et al. (2005)
5 ks Bootes

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

Penetrate large gas columns

Just CDF-N sources

High (quasar) luminosities
NGC5548
NGC3783
1 Zwicky 1

Moderate (Seyfert) luminosities
NGC6240

Low luminosities
NGC4051
NGC1068

3C 273
Even the deepest surveys are missing many AGNs

**Worsley et al. (2005)**

X-ray background is not fully resolved at >6 keV

**Tozzi et al. (2006)**

Modelled fraction of $L_X > 10^{41}$ erg/s AGNs in 1Ms CDF-S

Compton thick

**Treister & Urry (2005)**

Local Obscured AGN Ratio

Many of these “undetected” AGNs will be luminous C-thick objects: IXO will ID many but can we progress before then?
NGC1068: A Nearby Example

Matt et al. (1997)

Observed $L_X \sim 10^{41}$ erg/s
Intrinsic $L_X \sim 10^{43} - 10^{44}$ erg/s

Elvis & Lawrence (1988)

A low $L_X/L_{IR}$ ratio
(~2–3 orders of mag lower than typical AGN)

But the IR SED and optical lines indicate
a luminous obscured AGN is present

Efstathiou et al. (1995)

Warm IR SED

Grimes et al. (1999)

UV/optical spectrum
With Spitzer (and in near future Herschel, SCUBA2, ALMA), we can make great progress in identifying X-ray undetected AGNs and discriminating between starbursts and AGNs.

AGNs typically have “warmer” IR SED, although sometimes AGNs can be buried in a starburst SED.

X-rays alone can often identify an AGN in a strongly starbursting galaxy (and provide black-growth cycle).

But we also need both deep X-ray and IR observations to identify potential C-thick AGNs.
Overview

- **Characterising the far-infrared properties of distant AGNs**
  
  Result - $L_{\text{IR}}/L_X$ increases with redshift for modest AGNs ($L_X \sim 10^{42}-10^{43}$ erg/s): either increase in AGN dust covering or star formation?

- **Identifying individual X-ray undetected/weak distant AGNs (typically heavily obscured systems)**
  
  Result - (potential) C-thick AGNs appear to be at least as common as unobscured AGNs at high redshift

- **Exploring AGN activity in distant star-forming galaxies**
  
  Result - luminous AGN fraction increases with star-formation rate (longer black-hole duty cycle) but overall mass accretion-star formation rate in agreement with local Universe
Characterising the far-infrared properties of distant AGNs
Characterising infrared properties of distant AGNs

Mullaney, DMA et al. submitted

- 70 µm data easier to interpret than 24 µm data but lower sensitivities.
- 1Ms CDF-S with X-ray spectral analysis from Tozzi et al. (2006): specifically \( L_{2-10\text{keV}} \) and \( N_H \)
- Only 30 of 266 detected at 70 µm
  - Use stacking analysis to derive average 70 µm flux densities.
Expectations based on $z\sim 0$ Swift–BAT AGN sample

Mullaney, DMA et al. submitted

- Sensitive to very hard X-rays (14-195 keV): Tuller et al. (2008); Winter et al. (2009)

- Same intrinsic properties as CDF-S AGNs ($N_H; L_{2-10\text{keV}}$) but at $z<0.1$ (compared to $z>0.5$)

- 36 have Spitzer-IRS (5-35 μm) to ID between SB/AGN-dominated SEDs and make high-z predictions
Predictions from z~0 Swift-BAT AGN sample

Mullaney, DMA et al. submitted

- 70/24µm colours can discriminate between AGN-dom and SF-dom sources out to z~1.5
- 70µm data gives robust infrared luminosity assessment irrespective of whether source is AGN-dom or SF-dom
Key result: evolution in $L_{\text{IR}}/L_X$ ratio with redshift

Mullaney, DMA et al. submitted

Evidence for increase in $L_{\text{IR}}/L_X$ for modest luminosity AGNs from both 70um AND 24um data:

Increase in AGN dust-covering factor?
- Tentative qualitative support for increased absorption with redshift from X-ray surveys (La Franca et al. 2005; Hasinger 2008) BUT increase implied here is far larger

Increase in star-formation?
- $L_{\text{IR}}/L_X$ of z=1-2 AGNs similar to z~2 submillimetre of Alexander et al. (2005), which is due to large star-formation fraction
Identifying individual X-ray undetected/weak distant AGNs
X-ray undetected mid-IR AGNs in z~2 galaxies

Stacked X-ray data of mid-IR galaxies in narrow bands

Very hard signal => significant fraction of obscured AGNs
(see also Fiore et al. 2008, 2009 amongst others)

Ground-breaking results, although there are significant caveats: (1) what fraction of stacked result is due to hard X-ray sources? (2) how many are C-thick AGNs? (3) how much star-formation contamination is there?
Working towards ID’ing individual distant C-thick AGN

With this more robust approach we ID 7 z~2 (likely) Compton-thick AGNs: not a large number but significant since these are the first z~2 sources (and remember only ~50 C-thick AGNs known to date!)
Progress is being made from a variety of studies

Individual distant C-thick (or heavily obscured) AGNs being identified using spectroscopy with variety of samples/redshifts:

- $z \approx 0.5$ SDSS obscured quasars (Vignali et al. submitted)
- $z \approx 1-3$ infrared-bright AGNs (Bauer et al. submitted) (Donley et al. in prep)
- $z \approx 0.5-2$ “IR warm” X-ray undetected objects (Alexander et al. in prep)

The consistent result coming from these works is that the potential C-thick AGN space density at high redshift is at least as large as the unobscured AGN space density, broadly consistent with X-ray background models (Gilli et al. 2007)
Exploring AGN activity in distant star-forming galaxies
AGN activity in distant starburst galaxies

Rafferty, Brandt, DMA et al. in prep

- Based on 70 um data in variety of deep fields (E-CDF-S; EGS)
- Identify AGN using X-rays and remove AGN contribution from infrared to estimate star-formation rates
- Takes into account sensitivity effects due to absorption

Black-hole growth cycle

![Graphs showing fraction of galaxies with an AGN vs. log $L_{0.5, 824}$ (erg s$^{-1}$)]
$z < 2$ AGN fraction as function of $L_{\text{IR}}$ and SFR

AGN fraction increases with both $L_{\text{IR}}$ and SFR (consistent with nearby ULIRGs and submm galaxies): long black-hole growth cycle

Average accretion rate and star-formation rate consistent with local black-hole-spheroid mass ratio

Rafferty, Brandt, DMA et al. (in prep)
Potential of deep Herschel surveys

Herschel (70-500um) extents wavelength coverage and sensitivity: discriminate between star formation and AGN processes

Detection rate of X-ray sources for Herschel GOODS survey at 100um

Mullaney, DMA et al. submitted
Summary

- $L_{IR}/L_X$ of modest-luminosity AGNs ($L_X \sim 10^{42}-10^{43}$ erg/s) evolves with redshift:
  - \( \sim 5-20\times \) higher at $z>1$... not clear if increase is due to AGN activity or star formation; $L_{IR}/L_X$ constant for higher-luminosity AGNs ($L_X \sim 10^{43}-10^{44}$ erg/s)

- Variety of studies working towards identification of individual (potentially) C-thick distant AGNs using mid-IR/optical spectroscopy
  - general consensus is that there are at least as many C-thick AGNs as unobscured AGNs at high redshift

- Luminous AGN fraction in distant star-forming increases with star-formation rate but average mass accretion rate vs star formation rate is consistent with local black-hole-spheroid mass ratio

Improved sensitivity and broader wavelength coverage of Herschel (and SCUBA2) offers great potential to extend these studies to identify accurately between AGN and star-forming SEDs and to identify (potential) distant Compton-thick AGNs