Tracing the evolution of obscured AGN via measurements of the X-ray luminosity function with

Chandra ...

Aird et al. (2015a), MNRAS, 451, 1892
Alison Coil, Antonis Georgakakis, Kirpal Nandra, Guillermo Barro, Pablo Perez-Gonzalez

... and NuSTAR

David Alexander, Agnese Del Moro, George Lansbury, James Mulllaney, Fiona Harrison, Dan Stern, Francesca Civano, Ryan Hickox... and the NuSTAR Extragalactic surveys team

James Aird (Institute of Astronomy, University of Cambridge)
Tracing the evolution of absorbed AGN via measurements of the X-ray luminosity function (XLF) and unabsorbed Aird et al. (2015a)
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- Compare the evolution of absorbed and unabsorbed AGN across a wide range of luminosities and redshifts => different populations?
- Assess the importance of “hidden” black growth

Aird et al. (2015a)
What are the most effective techniques for identifying heavily obscured and Compton-thick AGN?
X-rays are the **worst** way of identifying heavily obscured and Compton-thick AGN
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(.... except for all the others)
The effects of absorption on the X-ray spectrum

$N_H \lesssim 10^{21}$ cm$^{-2}$
The effects of absorption on the X-ray spectrum

$N_H = 3 \times 10^{22} \text{ cm}^{-2}$
The effects of absorption on the X-ray spectrum

$N_H = 3 \times 10^{23} \text{ cm}^{-2}$
The effects of absorption on the X-ray spectrum

Soft band
(observed 0.5-2keV)

Hard band
(observed 2-7keV)

Compton-thick

$N_H = 3 \times 10^{24} \text{ cm}^{-2}$
Effects of absorption - $L_X$ and $N_H$ constraints for a single Chandra detection

Aird et al. (2015a)

- Includes uncertainty from Poisson counts and spectral parameters

A given Chandra detection *could* be a heavily absorbed or Compton-thick AGN, but would have to be a much higher luminosity source (thus rarer)
Effects of absorption - $L_X$ and $N_H$ constraints for a single Chandra detection

- Adopt samples of ~3000 hard X-ray detections at ~4500 soft X-ray detections from deep+wide Chandra surveys (CDFS, CDFN, AEGIS, COSMOS, Bootes) + wide-area surveys from ASCA and ROSAT
- Assume no a priori knowledge of absorption for any individual detection.
- Treat hard and soft detections as independent samples and find model for the overall X-ray luminosity and $N_H$ distribution that reconciles both samples

Includes uncertainty from Poisson counts and spectral parameters

Aird et al. (2015a)
Modeling XLFs of unabsorbed and absorbed AGNs

• We model the XLFs of unabsorbed \((N_H < 10^{22} \text{ cm}^{-2})\) and absorbed \((N_H > 10^{22} \text{ cm}^{-2})\) AGN as independent, evolving double-power law functions

• Seek a model that can simultaneously describe both the hard-band and soft-band Chandra samples, once absorption biases accounted for

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**Model XLFs of unabsorbed and absorbed AGNs**

![Graph showing the density evolution of XLFs at z = 0.1](image-url)
Modeling XLFs of unabsorbed and absorbed AGNs

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Model XLFs of unabsorbed and absorbed AGNs

**N_H** distribution

\( (+ 3 \text{ additional parameters}) \)

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**N_H** distribution

\( \log L_X = 44, z = 0.1 \)

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![Graph showing XLFs of unabsorbed and absorbed AGNs with constraints and likelihood evaluation steps.](image-url)
Modeling XLFs of unabsorbed and absorbed AGNs

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Model XLFs of unabsorbed and absorbed AGNs $\rightarrow$ $N_H$ distribution (+ 3 additional parameters) $\rightarrow$

fold through constraints from the observed soft-band and hard-band samples; evaluate likelihood

refine model
X-ray luminosity function - hard + soft bands

Including absorption

With corrections for absorption, estimates from hard and soft bands agree

Aird et al. (2015a)
Model for the evolution of the unabsorbed vs. absorbed XLF

Aird et al. (2015a)

- XLF of unabs. and abs. AGN are different:
  Abs. XLF has lower $L_\star$, higher normalization => absorbed AGN dominate at lower luminosities

- Broadly similar evolution (at least to $z \sim 2$):
  strong luminosity evolution
  + overall density evolution
  + mild flattening of faint-end slopes

- Evolution of shape of total XLF driven by changing mix of unabs. vs. abs.
The fraction of absorbed AGNs

• Reproduce luminosity-dependence of absorbed fraction, $f_{\text{abs}}$ due to differences in $L_*$ and $\gamma_1$
  (fraction of absorbed $N_H=10^{22-24}$ cm$^{-2}$ relative to all Compton-thin, $N_H<10^{24}$ cm$^{-2}$)

• Transition shifts in redshift due to luminosity evolution of both unabsorbed and absorbed XLFs

• Slight differences in relative evolution of normalization (K) -> increase in $f_{\text{abs}}$ for high $L$ with $z$?

Aird et al. (2015a)
Evolution of unabsorbed vs. absorbed XLF

- Strong luminosity evolution => higher Eddington ratios at higher $z$ or higher BH mass?
- Density evolution => changes in rate of AGN triggering?
- Differences in the evolution of normalization and $L_\ast$ indicative of different physical mechanism for triggering of (some fraction of) unabsorbed vs. absorbed AGN?
• X-ray Luminosity Functions of both unabsorbed and absorbed AGNs undergo strong evolution in luminosity and density

• Differences between the break luminosities ($L_*$), normalizations ($K$) and faint-end slopes ($\gamma_1$) of unabsorbed and absorbed AGN XLFs lead to the luminosity and redshift dependence of the fraction of absorbed AGNs ($f_{\text{abs}}$).

• The total XLF of AGNs (combining unabsorbed and absorbed populations) undergoes a complicated evolution with redshift, primarily driven by the changing mix of unabsorbed and absorbed AGNs.

Aird et al. (2015a)
First direct measurements of the rest-frame 10-40 keV luminosity function at z>0.1 with NuSTAR

Aird et al. (2015b)
NuSTAR extragalactic surveys program

Aird et al. (2015b)

- Use data from the ECDFS, EGS and COSMOS fields (see talk by Agnese Del Moro)
- Subset (~5 deg$^2$) of the serendipitous survey (see talk by George Lansbury)
- Define a sample of 97 X-ray sources detected at 8-24 keV
The effect of absorption on the NuSTAR 8-24 keV band

- 8-24 keV band is relatively unaffected by Compton-thin column densities
- But, if a source is Compton-thick then it must be higher luminosity

Aird et al. (2015b)
The effect of absorption on the NuSTAR 8-24 keV band

• 8-24 keV band is relatively unaffected by Compton-thin column densities

• But, if a source is Compton-thick then it must be higher luminosity

• Apply priors based on Aird+15a $N_H$ function (and also Ueda et al. 2014) to account for “unknown” level of absorption

• Down-weights Compton-thick columns as high-L sources are rare!

Aird et al. (2015b)
Measurements of the rest-frame 10-40keV luminosity function with NuSTAR

Aird et al. (2015b)

Find slight (but significant) differences in the binned measurements when using the Ueda+14 vs. Aird+15a $N_H$ functions to correct for absorption - what is going on?
Comparing intrinsic and predicted \(N_H\) functions

\[
\log(L_{10-40\text{keV}}/\text{erg s}^{-1}) = 43.7 \\
\log(L_{10-40\text{keV}}/\text{erg s}^{-1}) = 44.4 \\
\log(L_{10-40\text{keV}}/\text{erg s}^{-1}) = 45.0
\]

intrinsic (evaluated at median for bin)

predicted (throughout bin, accounting for NuSTAR sensitivity)

\(N_{\text{obs}}\)
Comparing intrinsic and predicted $N_H$ functions

Aird+15a model has larger number of heavily obscured sources ($N_H=10^{23-24}$ cm$^{-2}$), smaller $f_{C\text{thick}}$

<table>
<thead>
<tr>
<th>intrinsic (evaluated at median for bin)</th>
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<tr>
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<tr>
<td>$z=0.28$</td>
<td>$z=0.75$</td>
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<tr>
<td>$z=1.51$</td>
<td>$z=0.75$</td>
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- $U14 \ N_{\text{mdl}}=24.4$
- $A15 \ N_{\text{mdl}}=34.0$
- $\ N_{\text{obs}}=31.4$

- $U14 \ N_{\text{mdl}}=18.4$
- $A15 \ N_{\text{mdl}}=29.3$
- $\ N_{\text{obs}}=33.4$

- $U14 \ N_{\text{mdl}}=16.1$
- $A15 \ N_{\text{mdl}}=21.2$
- $\ N_{\text{obs}}=29.3$
Comparing intrinsic and predicted $N_H$ functions

Aird+15a model has larger number of heavily obscured sources ($N_H=10^{23-24}$ cm$^{-2}$), smaller $f_{Cthick}$

Strong bias against detection of Cthick sources, but not heavily obscured => larger correction to XLF when assuming Ueda+14
Measurements of the rest-frame 10-40keV luminosity function with NuSTAR

Alternatively, assuming stronger reflection ($R\approx 2$) for all AGN can brings Ueda+14 model into agreement with NuSTAR results

(inconsistent with spectral stacking results of Del Moro => $R\approx 0.5$?)
Comparison with Swift/BAT luminosity function

- Extrapolation of the models that successfully describe the high-z NuSTAR XLF to $z \approx 0$ overpredict the Swift/BAT measurements

- Hints at some evolution in the XLF, $N_H$ function, or spectral properties between higher redshifts probed by NuSTAR and $z \sim 0$ that is not accounted for by current models

- Similar discrepancy is also found for the NuSTAR number counts (Harrison, Aird et al., 2016, ApJ submitted)
Take home points

New measurements of XLF using latest Chandra surveys (Aird+15a)
- describes overall evolution of XLF of absorbed and unabsorbed AGN populations - *broadly* similar evolution in luminosity and density

First direct measurement of the XLF at >10keV and z>0.1, based on NuSTAR 8-24keV sample  (Aird+15b)
- Large population of $N_H=10^{23-24} \text{cm}^{-2}$ sources, *or* strong reflection
- comparison with Swift/BAT => some low-z evolution missing from current models