Obscuration/orientation effects in a sample of 0.5<z<1 3CRR sources observed by Chandra

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Despite their intrinsically bright, multi-wavelength emission, an unknown fraction of active galactic nuclei (AGN) remain obscured, their nuclei invisible due to orientation-dependent obscuration by massive amounts of material. One way to select AGN samples that are orientation-unbiased (although limited to radio-loud sources) is low frequency radio, where the selection is based on extended radio lobes. Radio data also provide an independent estimate of orientation via the radio core fraction (R_{CD}).

We extend our studies of a complete, low radio frequency (178 MHz) selected, Chandra observed sample of high-redshift (1<z<2) 3CRR sources (Wilkes et al. 2013) to medium redshifts (0.5<z<1). This complete and orientation unbiased sample includes: 13 quasars, 22 narrow-line radio galaxies (NLRGs) and 1 low-excitation radio galaxy (LERG), with matched radio luminosities (log L(178MHz)~35.3-36.5 erg/s/Hz). The quasars show high X-ray luminosities (log L_X(0.5-8keV)~45-46 erg/s), soft X-ray hardness ratios (HR<0), and high radio core fractions, indicating low obscuration (N_H < 10^{22}cm^{-2}) and face-on inclination. NLRGs, show 10-1000 times lower X-ray luminosities, a wide range of hardness ratios, and lower radio core fractions, implying a range of obscuration (N_H > $10^{20.5}$cm^{-2}) and higher inclination angles. These properties together with the observed trend of increasing intrinsic N_H with decreasing radio core fraction are roughly consistent with orientation-dependent obscuration as in Unification models. However, this sample includes a new population, not seen at high redshift: NLRGs with unusually low intrinsic N_H (< 10^{22}cm^{-2}) and viewed at intermediate angles, skimming the edge of the accretion disk/torus. Analysis of their properties suggests a lower L/L_{Edd} ratio compared to NLRGs viewed at similar inclination angles but with higher N_H. Hence a simple Unification model cannot fully explain the properties of the 3CRR sources at medium-z (as it did at high-z) and needs to include a range of L/L_{Edd} ratios. Similarly to the high-z 3CRR sample ~22% of the sources in the medium-z sample are Compton-thick, showing high L([OIII])/L_X(2-8keV) ratios.

1. Sample

Complete, flux limited (10 Jy at 178 MHz), 3CRR sample (Laing et al. 1983) of 36 radio sources with 0.5 < z < 1. Includes 13 quasars, 22 NLRGs and 1 LERG (8 are compact steep-spectrum sources - CSS,; no beamed sources). At low frequencies (dominated by emission from radio lobes) radio selection results in a sample with little/no orientation bias.

All sources are FRIIs = all are AGN.

Radio-core fraction $R_{CD} = \frac{L_{core}(5GHz)}{L_{lobe}(5GHz)}$ provides an estimate of orientation.

Great sample to study orientation effects in AGN (although only 10% of AGN are radio-loud).

We compare this sample with the high-*z* (1<*z*<2) 3CRR sample (38 sources) from Wilkes et al. (2013).

L_{radio}(178MHz)

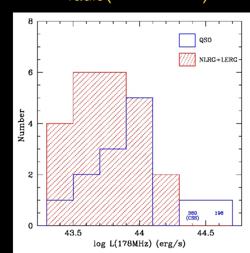


Fig. 1a Total, extended, rest-frame 178 MHz radio luminosity.

Quasars and NLRGs match in L_{radio} —> similar intrinsic Ls

L_X(2-8keV)

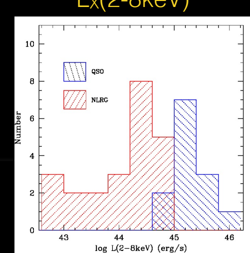
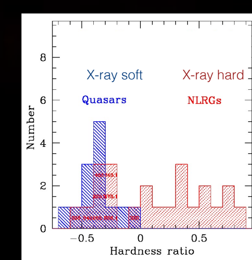


Fig. 1b Nuclear hard-X-ray (2-8keV) luminosity, *uncorrected* for intrinsic absorption.

NLRGs are 10-1000x fainter than quasars in L_X —> larger obscuration in NLRGs.

2. X-ray Hardness Ratios (HR)



X-ray Hardness Ratio: $HR = \frac{H-S}{H+S}$

(H = 2-8 keV counts, S = 0.5-2 keV counts) calculated using BEHR (Park+ 2006)

Quasars:
soft HR, X-ray bright -> low obscuration (N_H)

NLRGs:
wide range of HR, X-ray faint -> range of N_H

3. X-ray Hardness Ratio vs. N_H

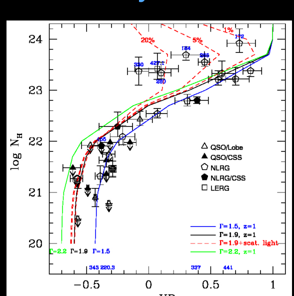


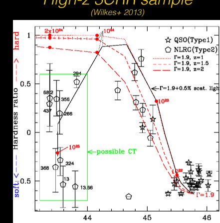
Fig. 3 The intrinsic N_H, from X-ray spectral fitting (when available), as a function of the observed hardness ratio (HR) in our sample. For comparison, are shown models of an absorbed (N_H=10^{20}–10^{24}cm^{-2} range) power law with Γ = 1.5 (blue), 1.9 (black), 2.2 (green), at redshift 1. Dashed red lines plot models of the absorbed power law with Γ = 1.9 + 1%, 5% or 20% scattered intrinsic AGN light.

HR becomes larger (harder) with increasing N_H

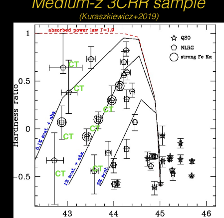
But: 5 NLRGs with highest N_H lie off the absorbed power law models and require additional soft excess emission from: scattered intrinsic light, extended X-ray emission or jet emission.

4. HR not a good indicator of high N_H

High-z 3CRR sample (Wilkes+ 2013)



Medium-z 3CRR sample (Kuraszkiewicz+2019)



When obscuration increases-> L_X decreases and HR becomes harder (red models). But highly obscured NLRGs (with lowest L_X) require an additional soft component (black model). Hence ~20% of sources (with high N_H) at high-*z* have L_X underestimated by 10-1000 if HR is used -> lower obscured AGN fraction and steeper LF.

At medium-*z* X-ray spectra are more complex as *Chandra* probes softer-X-rays.

5. Correlations with R_{CD} / Unification

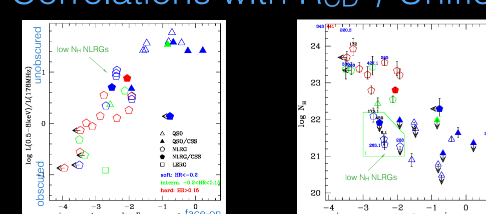


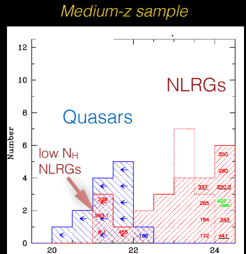
Fig. 6 The ratio of the Xray luminosity, not corrected for intrinsic N_H to the total radio luminosity at 178 MHz *(left)* and intrinsic equivalent hydrogen column density N_H, estimated from X-ray spectral fits *(right)* as a function of the radio core fraction R_{CD}.

Strong dependence of L_X/L_{radio} and N_H on R_{CD} is consistent with orientation dependent obscuration as in Unification models.

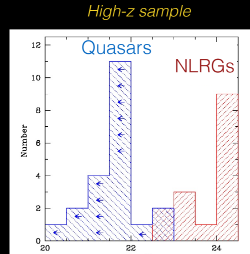
But 5 low-N_H (<10^{22} cm^{-2}) NLRGs don't fit as NLRGs with a large range of intrinsic N_H=$10^{21.0-23.5}$ cm^{-2} exist at similar viewing angles (-3 < log R_{CD} < -2). These low-N_H NLRGs have high L_X/L_{radio}, soft HR, low 30μm emission) and possibly low L/L_{Edd}.

6. N_H distribution

Medium-z sample



High-z sample

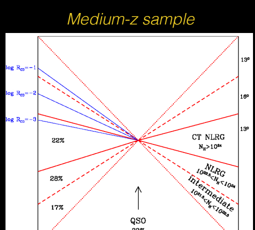


Quasars: low N_H < $10^{22.5}$ cm^{-2} (both samples)
NLRGs: N_H > $10^{22.5}$ cm^{-2} (high-*z*)
N_H > 10^{21} cm^{-2} (medium-*z*)

New population at medium-*z:* low-N_H NLRGs.

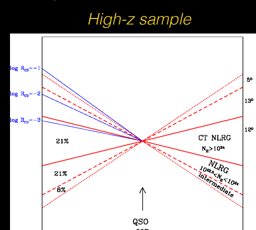
7. Geometry

Medium-z sample



torus puffier and clumpier
range of L/L_{Edd}

High-z sample



compact torus
high L/L_{Edd} - higher gas supply?

8. L/L_{Edd}

At lower L/L_{Edd} circumnuclear dust+gas clouds have a broader range of N_H (Fabian+ 2008) and the dusty torus becomes clumpier and puffier (Ricci+ 2018) resulting in lower mid-IR emission —> low-N_H NLRGs possibly have lower L/L_{Edd} —> the medium-*z* 3CRR sample has a large range of L/L_{Edd} extending to lower values compared to the high-*z* sample, which has high L/L_{Edd} due to higher gas supply at high-*z*

9. Compton-thick (CT) sources

L([OIII]) tracks radio and intrinsic X-ray Ls in broad and narrow-lined AGN and is used as a measure of intrinsic L_X (Jackson & Rawlings 1997, Mulchaey+ 1994).

High L([OIII])/L_X(2-8keV) and/or high L(30μm)/L_X(2-8keV) suggest a Compton-thick (CT) source. We find 6 CT+2 borderline CT candidates = 22% of the medium-*z* sample (similar to 23% at high-*z* sample).

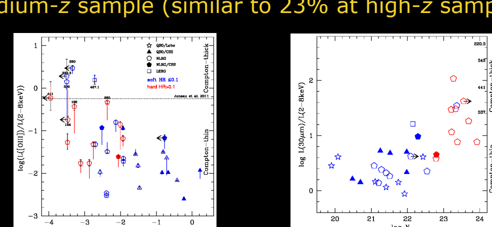


Fig. 7 Left: The ratio of L([OIII]) to hard 2-8keV X-ray luminosity, not corrected for intrinsic N_H, as a function of radio core fraction R_{CD}. CT AGN lie above the dotted line of Juneau+ (2011). *Right:* Ratio of mid-IR 30μm (*Herschel*) to hard X-ray luminosity as a function of intrinsic N_H. For N_H >10^{23}cm^{-2} the L(30μm)/L_X ratio dramatically increases.

Summary

We study a complete, medium redshift (0.5<*z*<1), low frequency (178MHz) radio selected, and so unbiased by orientation sample of 3CRR sources which includes: 13 quasars, 22 NLRGs and 1 LERG matched in L(178MHz).

Quasars are soft and bright in X-rays and have high R_{CD} implying low obscuration and face-on inclination.

NLRGs have 10-1000x lower L_X(2-8keV), wide range of X-ray hardness ratios, and low R_{CD} implying wide range of obscuration (N_H > $10^{20.5}$ cm^{-2}) and high inclination.

The observed trend of increasing obscuration with decreasing radio core fraction R_{CD} is consistent with orientation-dependent obscuration as in Unification models. However, a population of low-N_H (<10^{22} cm^{-2}) NLRGs, is found at similar viewing angles as NLRGs with higher N_H ($10^{22-23.5}$) implying a wider range of L/L_{Edd} ratios in the medium-*z* sample (extending to lower values) than in the high-*z* sample.

8 NLRGs (22% of sample) show CT L([OIII])/L_X(2-8keV) and/or L(30μm)/L_X(2-8keV) ratios.

The ratio of unobscured (N_H<10^{22}) to obscured (N_H>10^{22}) sources is 1 (same for high-*z*). Unobscured/Compton-thin/Compton-thick ratio=2:1.5:1 (high-*z* sample: 2.5:1.4:1)

Background: Cygnus A (3C 405) - one of the brightest and closest (600 million light-years away) sources visible in radio. Radio emission extends to either side nearly 300,000 light-years powered by jets of relativistic particles. Hot spots mark the ends of the jets impacting surrounding cool, dense intergalactic medium. Image credit: NSF/NRAO/AUI/VLA