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.

We extend our studies of a complete, 178 MHz radio flux-limited, 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)~43.5-44.5). The quasars show high X-ray luminosities Lx(0.3-8keV)~45-46, soft hardness ratios (HR<0), and high radio core fractions, indicating low obscuration (log N_H < 22) and face-on inclination. NLRGs, have lower observed X-ray luminosities (Lx~43-45), a wide range of hardness ratios, and lower radio core fraction, implying a range of obscuration (log N_H > 20.5) and higher inclination angles. These properties together with the observed trend of increasing 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: 1/4 of the NLRGs have extremely low NH (log NH < 22, i.e. are X-ray Type 1), show high for NLRGs Lx/Lr ratios, soft hardness ratios, and weak near-to-mid-IR emission and require lower L/Ledd ratios resulting in clumpier and cooler torus. 22% of sample show Compton-thick [OIII]/L(2-8keV) ratios (similar to the high-z sample).

1. Sample

The 3CRR catalog (Laing et al. 1983) includes 180 radio sources (quasars and radio galaxies) up to z=2.5 and is complete to a flux of 10 Jy at 178MHz. At low frequencies radio emission is dominated by emission from radio lobes (which are optically thin and emit nearly isotropically), resulting in a sample with little/no orientation bias.

We focus here on a complete, medium redshift (0.5<z<1) 3CRR sample of 36 radio sources (13 quasars, 22 NLRGs and 1 LERG; includes 8 compact steep-spectrum sources - CSS). Great sample to study orientation effects in AGN (but only 10% of AGN are radio-loud).

All sources are FRIIs = all are AGN.

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

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

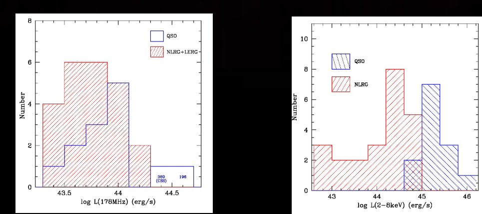


Fig.1 A comparison of the distributions of total, extended rest-frame 178 MHz radio luminosity *(left)* and hard-band (2-8keV), nuclear X-ray luminosity, uncorrected for intrinsic absorption *(right)*. Quasars (QSOs) are plotted in blue and NLRGs in red.

Quasars and NLRGs match in L_{radio} (1dex range).

Do not match in observed hard X-ray luminosities. NLRGs are 10-1000x fainter than quasars —> larger obscuration in NLRGs.

2. Hardness Ratios (HR)

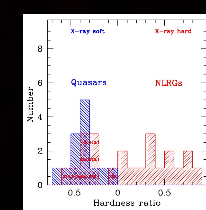


Fig.2 Histograms of the X-ray hardness ratios (calculated using BEHR) for quasars (blue) and NLRGs (red)

Hardness ratio: $HR = \frac{H - S}{H + S}$

H - hard (2-8keV) counts
S - soft (0.5-2keV) counts

Quasars: X-ray bright, soft HR -> low obscuration i.e. N_H

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

3. HR vs. N_H

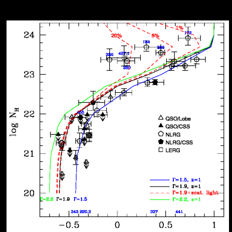
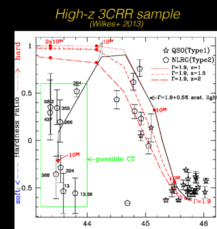


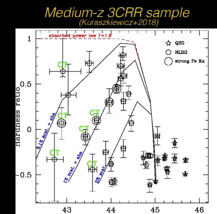
Fig.3 Intrinsic N_H from X-ray spectral fitting (when available) as a function of the observed hardness ratio (HR). For comparison, we show the relationship between N_H and HR for an absorbed power law, assuming Γ = 1.5 (blue), 1.9 (black), 2.2 (green), at redshift 1 (solid lines). In red an absorbed power law with Γ = 1.9 + 1%, 5% or 20% scattered intrinsic AGN light is plotted.

HR becomes harder with increasing N_H

Five high N_H NLRGs (3C172,184,230,265,330) lie off the absorbed power law curves and require additional soft excess emission from either scattered intrinsic light, extended X-ray emission or jet emission.

4. HR not a good N_H indicator





Higher obscuration -> lower observed L_X, harder HR

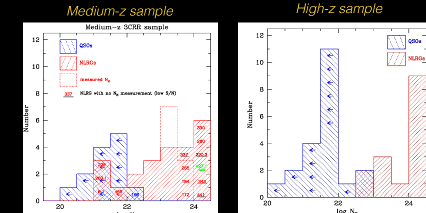
Lowest L_X (highly obscured) sources require an additional softer component.

HR is not a good indicator of N_H at high obscuration.

For ~20% of high-z sources L_X is underestimated by 10-10^3 when using HR for N_H correction. This will result in lower obscured fraction and steeper LF.

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

5. N_H distribution



Quasars: low N_H < $10^{22.5}$ cm^{-2} in both samples.

NLRGs:
N_H > $10^{22.5}$ cm^{-2} (high-z)
N_H > 10^{21} cm^{-2} (medium-z)

Note the 5 low N_H NLRGs (=1/4 of all NLRGs) in medium-z sample not present at high-z.

6. Correlations with R_{CD}

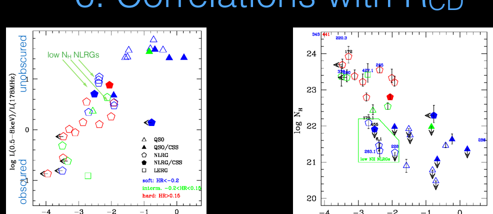


Fig.6 The ratio of observed X-ray to total radio luminosity *(left)* and intrinsic equivalent hydrogen column density N_H, estimated from X-ray spectral fits *(right)* as a function of the radio core fraction R_{CD}.

Strong dependence between R_{CD} and L_X(obs)/L_{radio} and N_H -> consistent with orientation dependent obscuration as in Unification models.

But 5 low N_H (<10^{22}) NLRGs don't fit, as NLRGs with a large range of N_H(int) = $10^{21.0\text{-}23.5}$ exist at similar viewing angles (-3 < log R_{CD} < -2).

Low N_H NLRGs show: high L_X/L_{radio}, soft HR, low mid-IR (30μm) emission, and low specific star formation (Westhues et al. 2016).

The medium-z 3CRR sample possibly has a range of L/L_{Edd} ratios extending to lower values than in the high-z sample. At lower L/L_{Edd} clouds with a range of N_H may exist (extending to lower N_H - Fabian et al. 2008) and the dusty torus becomes clumpier and puffier (Ricci+ 2018) resulting in lower mid-IR emission.

7. Compton-thick (CT) sources

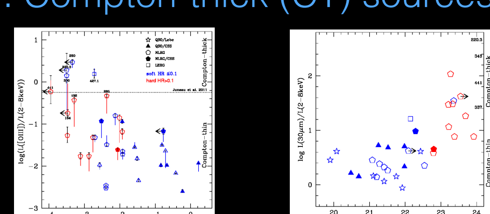


Fig.7 Left: The ratio of L[OIII] to hard (2-8keV) X-ray luminosity, not corrected for N_H(int), as a function of radio core fraction R_{CD}. For sources with no measured L[OIII] values were estimated from measurements of L[OII] following Grimes et al. (2004). Compton thick AGN lie above the dotted line (Juneau et al. 2011). *Right:* The 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.

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

High L([OIII])/L(2-8keV) and high L(30μm)/L(2-8keV) suggest a Compton-thick (CT) source.

We find 6 (3C 220.3*,280,330,427.1,343,441) CT + 2 borderline CT candidates = 22% of the medium-z sample (similar to 25% at high-z sample).

*3C 220.3 (z=0.685) is lensing a submm galaxy with a hidden quasar at z=2.221 (Haas et al. 2015).

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_{radio}.

Quasars have high L_X(2-8keV), soft hardness ratios, and high R_{CD} implying low obscuration (N_H < $10^{22.5}$cm^{-2}) and face-on inclination.

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

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}) NLRGs (14% of sample), is found at similar viewing angles as NLRGs with higher N_H ($10^{22\text{-}23.5}$). This implies a wider range of L/L_{Edd} ratios in the medium-z sample (extending to lower ratios) than in the high-z sample.

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