Not so close to the event horizon: latest results on circumnuclear matter in SMBHs

Andrea Marinucci

From the Dolomites to the event horizon: sledging down the Black Hole potential well (4th edition)

Sexten 2017 – 11 July 2017
Outline

- Introduction
  (far away from the event horizon)

- Sub-pc absorption

- Absorption/reflection on the pc-scale

- Hard X-ray view of Seyfert 2 galaxies

- Conclusions
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Introduction

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- high-ionization coronal lines (optical)
- absorbed/transmitted component (X-ray)
- scattered/reflected component (X-ray)
- thermal emission from dust (infrared)
- jet synchrotron emission (radio)
- scattered/polarized broad lines (optical)
- ionization cone narrow lines (optical)

Farrah+16
Geometry ($c_F$, inclination) and composition (number of clouds, distance) of the cold circumnuclear reprocessor?

Farrah+16
The geometry of absorption

The absorber must break the symmetry of the polarization angles: a “torus” is the most natural configuration.

The size of the torus was postulated to be on the parsec scale (Krolik & Begelman, 1986, 1988):

- Large enough to obscure the BLR
- Small enough not to obscure the NLR

Antonucci & Miller, 1985

Polarization and the Hidden Nucleus of NGC 1068

Intensity

Polarized intensity

Antonucci & Miller, 1985

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The geometry of absorption

While the AGN unified picture remains valid in its more general sense (the presence of non-spherically symmetric absorbers at the origin of the type 1/type 2 dichotomy), several new observations and models, mostly in the X-ray and infrared domain, suggest that multiple absorbers are present around the central source, on quite different physical scales (e.g. Bianchi, Maiolino & Risaliti 2012)
The geometry of absorption

On the sub-pc scale, dust-free gas along the line of sight has been observed through X-ray absorption variability: part of the observed X-ray absorption is due to BLR clouds.

On the parsec scale, and down to the dust sublimation radius, the “standard” torus has been directly imaged in a few sources with interferometric techniques, and its presence is suggested by X-ray reflection properties, and dust reverberation mapping in the near-IR.

On scales of hundreds of parsecs, or even larger (galactic dust lanes), circumnuclear matter has been imaged, and is clearly responsible of the “type 2” (in optical/UV) or “absorbed” (in X-rays) classification of a significant fraction of AGN.
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Sub-pc absorption

X-ray absorption variability is common in AGN: the circumnuclear X-ray absorber (or, at least one of its components) must be clumpy and located at subparsec distance.

$N_H$ variations ($10^{22}$–$10^{23}$ cm$^{-2}$) on scales from months to hours are found in a growing number of sources (Risaliti et al. 2002, Torricelli-Ciamponi et al. 2014).

NGC 1365 (Risaliti et al. 2005, Rivers et al. 2015), NGC 7582 (Bianchi et al. 2009), Swift J2127.4 (Sanfrutos et al. 2013), MCG-6-30-15 (Marinucci et al., 2014).
NGC 1365 shows absorption variability down to ~10 hours: absorption is due to clouds with velocity $>10^3$ km s$^{-1}$, at distances of $\sim10^4$ $R_\odot$. Their physical size and density are $\sim10^{13}$ cm and $\sim10^{10}$-$10^{11}$ cm$^{-3}$.

All these physical parameters are typical of BLR clouds: the X-ray absorber and the clouds responsible for broad emission lines in the optical/UV are one and the same.

The obscuring clouds appear to have a "cometary" shape: a high-density head, and an elongated, lower-density tail.

Maiolino et al. 2010
Sub-pc absorption (Swift J2127.4) – $a \sim 0.6$

Sanfrutos et al. 2013
Sub-pc absorption (Swift J2127.4) – $a \sim 0.6$

Sanfrutos et al. 2013

$T_{\text{occ}} \sim 70 \pm 30 \text{ ks}$

$C_f = 0 - 0.4$

$N_H = 2 \times 10^{22} \text{ cm}^{-2}$

$v_K \sim 2000 \text{ km/s}$

$R > 4 \times 10^{16} \text{ cm}$

$n \sim 2 \times 10^9 \text{ cm}^{-3}$

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Sub-pc absorption (MCG-6-30-15) – $a \sim 0.9$

Marinucci et al. 2014
Sub-pc absorption (MCG-6-30-15) – $a \sim 0.9$

$T_{\text{occ}} \sim 20 \text{ ks}$

$\Delta C_f = 0.32$

$v_K \sim 3000 \text{ km/s}$

$R = G M_{\text{BH}} v^{-2} = 7 \times 10^{15} \text{ cm} = 10^4 R_g$

$n \sim N_H / D \sim 7 \times 10^9 \text{ cm}^{-3}$

Marinucci et al. 2014
If the covering factor and the optical depth of the BLR are large enough, a significant fraction of the iron Kα emission line should be produced there.

NGC 7213 has no Compton reflection (Bianchi et al. 2003, 2004, Lobban et al. 2010, Ursini et al. 2015): the observed iron line cannot be associated to a Compton-thick material, like the torus or the disc.

Simultaneous optical/X-ray (Chandra HEG) observations show that the FWHM of the iron line Kα and that of the Hα are both ~2500 km/s.

The iron Kα in NGC7213 is produced in the BLR! (see also NGC2110: Marinucci et al 2015 and Ark 120: ~5000 km/s, Nardini et al. 2016)
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Early evidence for a circumnuclear dusty medium on (sub)parsec scales was obtained from near-IR studies, which revealed the presence of very hot dust, close to the sublimation temperature (Storchi-Bergmann et al. 1992, Alonso-Herrero et al. 2001, Oliva et al. 1999)

Extensive reverberation observational campaigns also confirmed the expected $L^{1/2}$ dependence of the sublimation radius (Suganuma et al. 2006)
Mid-IR interferometry of NGC 1068 is consistent with a two-component dust distribution: an inner (0.5 pc) elongated hot (T>800 K) component, and a more extended (3-4 pc), less elongated colder (T~300 K) component (Jaffe et al. 2004)

**Most of the absorption is located outside 1 pc.**

A similar result was found for Circinus: again two components, an inner and more compact (0.4 pc), and an outer (2 pc) component.

No significant differences are found between type 1 and 2 sources and the size of the dusty emitter scales with the square root of the luminosity (Tristram et al. 2009, 11; Kishimoto et al. 2011)
Compton-thick material with large covering factor is needed by the ubiquitous presence of the iron line and the Compton reflection component (Perola et al. 2002; Bianchi et al. 2004, 2009).

The line, typically unresolved (FWHM < thousands km/s), must be produced far (BLR/torus/NLR). Current X-ray satellites resolve its FWHM only in a few objects and with limited information, generally leading to inconclusive estimates on its location (Nandra et al. 2006, Shu et al. 2011).

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**Pc-scale absorption/reflection**

Nandra, 2006

Shu et al. 2011
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Nevertheless, strongly absorbed Seyfert 2 galaxies are the perfect laboratory for studying the circumnuclear cold material.

X-ray spectra of Compton-thick sources are completely dominated by reflection features, and they typically do not show any variability even on long time scales: the narrow iron line and the Compton reflection component are mostly produced on parsec-scale distance.

Fabian & Miniutti 2005
With Chandra we have the angular resolution to spatially resolve some of this systems.
Imaging analysis with Chandra (~ 420 ks) revealed that the Iron Kα and the associated Compton reflection continuum are spatially extended on scales of hundreds of parsecs.

The unresolved, nuclear emission confirms to remain constant throughout the 13 years of monitoring. The Equivalent Width of the neutral Fe Kα emission line is 2.7±0.5 keV.
Pc-scale absorption/reflection (NGC 4945)

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reg. 1</th>
<th>Reg. 2</th>
<th>Reg. 3</th>
<th>Reg. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{p,extrav}}$</td>
<td>$0.40 \pm 0.03$</td>
<td>$0.39 \pm 0.03$</td>
<td>$0.37 \pm 0.08$</td>
<td>$0.12 \pm 0.02$</td>
</tr>
<tr>
<td>Fe Kα Energy</td>
<td>$6.44 \pm 0.05$</td>
<td>$6.43 \pm 0.03$</td>
<td>$6.40 \pm 0.03$</td>
<td>$6.40^{+0.02}_{-0.03}$</td>
</tr>
<tr>
<td>Fe Kα Flux</td>
<td>$0.05 \pm 0.02$</td>
<td>$0.08 \pm 0.02$</td>
<td>$0.09 \pm 0.03$</td>
<td>$0.07 \pm 0.02$</td>
</tr>
<tr>
<td>Fe Kα EW</td>
<td>$0.45^{+0.30}_{-0.20}$</td>
<td>$0.65^{+0.30}_{-0.25}$</td>
<td>$0.75^{+0.40}_{-0.25}$</td>
<td>$2.15^{+1.30}_{-0.85}$</td>
</tr>
<tr>
<td>Fe XXV Kα Energy</td>
<td>$6.65^{+0.03}_{-0.04}$</td>
<td>$6.66 \pm 0.07$</td>
<td>$6.65 \pm 0.06$</td>
<td>$6.60 \pm 0.10$</td>
</tr>
<tr>
<td>Fe XXV Kα Flux</td>
<td>$0.11 \pm 0.03$</td>
<td>$0.04 \pm 0.02$</td>
<td>$0.03 \pm 0.02$</td>
<td>$0.02 \pm 0.01$</td>
</tr>
<tr>
<td>Fe XXV Kα EW</td>
<td>$0.90 \pm 0.30$</td>
<td>$0.30 \pm 0.25$</td>
<td>$0.35 \pm 0.30$</td>
<td>$0.60^{+0.70}_{-0.45}$</td>
</tr>
<tr>
<td>$F_{3-10 \text{ keV}}$</td>
<td>$0.80 \pm 0.07$</td>
<td>$0.75 \pm 0.08$</td>
<td>$0.85 \pm 0.08$</td>
<td>$0.28 \pm 0.05$</td>
</tr>
<tr>
<td>C/d.o.f.</td>
<td>$37/51$</td>
<td>$65/40$</td>
<td>$28/38$</td>
<td>$26/31$</td>
</tr>
</tbody>
</table>
The Fe Kα EW, depends on the Fe abundance (Matt et al, 1997), on the angle $\theta$ between the polar direction and the line of sight (Matt et al., 1991; George & Fabian, 1991) and on the column density of the illuminated material (Yaqoob et al. 2010, Matt 2002).

We therefore used different models to retrieve the observed EWs of the Fe Kα in the nuclear region (2.7±0.5 keV) and in region 2 (0.65±0.30 keV).

**Pexmon**

$A_{fe} \text{ (Nucleus)} = 3.2\pm0.4$

$A_{fe} \text{ (Region 2)} = 0.8\pm0.5$

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**MYtorus**

![Diagram showing Pc-scale absorption/reflection (NGC 4945) with parameters for Pexmon and MYtorus models]
(Not so-)Pc-scale absorption/reflection

Mrk 3

Guainazz et al 2011

1" = 270 pc

Circinus

Marinucci et al. 2013

1" = 19 pc

NGC 1068

Young et al 2001

1" = 110 pc

ESO 428-G014

Fabbiano et al. 2017

1" = 112 pc
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Hard X-ray view of Seyfert 2 galaxies

Matt et al., 2003

Yaqoob & Murphy, 2010
Hard X-ray view of Seyfert 2 galaxies

Balokovic et al. 2013

Harrison et al. 2013
Swift/BAT 70-month catalog AGN

- some targeted programs

→ ~100 ks of NuSTAR exposure
→ simultaneous soft X-ray coverage

- mostly “snapshot” observations
→ short 15-25 ks exposures
→ simultaneous Swift/XRT (7 ks)

- typically ~5000 cts in total (500–10^6)

- not representative in general, but the Sy2 subsample can be made representative

Baloković et al., in prep.
Subsample of 120 Seyfert 2 galaxies

Baloković et al., in prep.
NuSTAR view of Seyfert 2s

→ with minor variations, used ubiquitously in the literature to describe Sy2 spectra

\[ R_{\text{int}} \text{ as a replacement for } R_{\text{pexrav}} \]

\[ R_{\text{int}} = \frac{L_{\text{reflection}}}{L_{\text{intrinsic}}} \text{ (10-50 keV)} \]

Balokovic et al., in prep.
NuSTAR view of Seyfert 2s

Detailed modeling: Rivers et al. 2015

NGC 7582

NGC 612

Two types:

1) $R_{\text{int}} > 1$
   Also seen in stacked spectra: Malizia et al. 2003, Ricci et al. 2011

2) “normal”

Baloković et al., in prep.
“Majority of local Swift/BAT-selected Seyfert 2 nuclei have an inhomogeneous borderline Compton-thick torus-like obscurer with a high covering factor.”
Baloković et al., in prep.
The variable absorber in NGC 1068

We observed NGC 1068 with a joint XMM-Newton and NuSTAR monitoring campaign, from July 2014 until February 2015.

Longer time-scales can be probed thanks to the two previous XMM-Newton observations performed in 2000 (Matt et al. 2003), and the NuSTAR observation performed in 2012 (Bauer et al. 2014).
The variable absorber in NGC 1068

No variability is found between the four XMM spectra, and with respect to the spectrum taken in July 2000.

The neutral Iron Kα line is constant within 5%. Although the intrinsic variability is unknown, this suggests that most of the line/reflection is produced far away.

The forbidden component of the OVII Kα line triplet is constant within 1%. We know that it is produced in an extended emission coincident with the NLR, but e.g. NGC5548 (Detmers et al. 2009).
Above ~15 keV, a clear excess (~30%) is present in the August 2014 NuSTAR spectra! Marinucci et al. 2016

This variation strongly suggests an unveiling event in NG1068 due to a change of the absorbing column density along the line of sight and/or a brightening of the intrinsic continuum.

We test this scenario adopting the Bauer+14 model to fit the multi-epoch data and leaving only the primary component ($N_H$ and flux) free to vary.
The intrinsic X-ray luminosity for the three NuSTAR observations is consistent with the ones inferred using other proxies ([OIII], mid-IR) if all the spectral difference can be attributed to a change in the absorbing column density, from $N_H \sim 10^{25} \text{ cm}^{-2}$ in 2012/2015 to $N_H \sim 6 \times 10^{24} \text{ cm}^{-2}$ in 2014.
We will start monitoring the source again on next August, trying to catch a new variation in the hard X-rays.
Conclusions

- Obscured AGN remain the perfect laboratory to study the circumnuclear environment (origin of the iron Kα line, location of the Compton absorbing/scattering material, Compton-thick eclipses)

- We have significant statistics with Chandra to resolve and study nearby Compton-thick sources, leading to important information on the reprocessing material on scales of hundreds of pc (geometry, extension)

- Hard X-ray surveys are of great importance to disentangle and characterize the reprocessed and primary continuum (and test self-consistent models for the torus)

- Still some surprises from the usual suspects (NGC 1068, MCG-6-30-15, Mrk 3, NGC 1365)
Recently, Bauer et al. (2014) analysed NGC 1068 using data from different observatories, including the 3-79 keV data from the NuSTAR 2012 observation. They interpreted the broadband cold reflected emission of NGC 1068 as originating from multiple reflectors with three distinct column densities.

The higher $N_H$ component ($N_{H,1} \approx 10^{25} \text{ cm}^{-2}$) contributes most to the Compton hump (and is also responsible for the total suppression of the intrinsic continuum), while the lower $N_H$ component ($N_{H,2} \sim 1.5 \times 10^{23} \text{ cm}^{-2}$) produces much of the neutral iron line emission.

Almost 30% of the neutral Fe Kα line flux arises from regions outside the central 140 pc and is clearly extended (see also Young et al, 2001; Ogle et al., 2003).