Dust in Active Galactic Nuclei: a close look at the torus and its surroundings

Almudena Alonso Herrero
The idea of a Unified Model for AGN was put forward by Antonucci & Miller in 1985.

The torus of dust and molecular gas is the key ingredient.
Importance of the dust-obscured AGN phase in galaxy evolution

(c) Interaction/“Merger”
- now within one halo, galaxies interact & lose angular momentum
- SFR rates to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(b) “Small Group”
- halo acquires similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently

(a) Isolated Disk
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- “Seyfert” fueling (AGN with M_{bh} -> 23)
- cannot redden to the red sequence

(d) Coalescence/(U)LIRG
- galaxies coalesce; violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but total stellar mass formed is small

(e) “Blowout”
- BH grows rapidly; briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible

(f) Quasar
- dust removed: now a “traditional” QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

(g) Decay/K+A
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant redshifted rapidly (E+A/K+A)
- “hot halo” from feedback
- sets up quasi-static cooling

(h) “Dead” Elliptical
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to “large group” scales: mergers become inefficient
- growth by “dry” mergers

Hopkins+2008
Different physical scales of dust in nuclear regions of Active Galaxies

Ramos Almeida & Ricci 2017

- Torus: a few to tens of parsecs
- Polar dust: up to a few hundred parsecs
- Circumnuclear disks: a few hundred parsecs to up to 1 kpc
Thermal IR emission of radio quiet AGN + angular resolution


García-González+2016, and templates from Mullaney+2011

- Ground-based imaging/spectroscopy: NIR AO (<0.1’’), MIR diffraction limited (~0.3’’)
- Interferometry (<0.1’’)
- MIR/FIR: SOFIA(~3’’), Herschel (3-10’’), ALMA (0.3-0.04’’)

Diagram showing QSO template, AGN accretion disk emission, and Dust emission.

Diagram showing normalized f/nu vs. rest-frame wavelength (microns) and normalized f/nu vs. rest-frame wavelength (mu m) with various galaxy labels and wavelength ranges.
Outline of the talk

What we have learned in the last ~5 years - an incomplete review and only for radio-quiet AGN

✦ A few surprises about the dusty molecular torus of nearby AGN
✦ A new paradigm: the dynamical torus
✦ Properties of the AGN dust: grains, dust composition, PAH
✦ Properties of the torus in distant AGN: dust covering factors and evolution
Structure of the torus (in 2013)

- Small torus sizes at $12\mu m$, ~3x smaller than expected Barvainis 1987
- No differences between type 1 and type 2
- Larger scatter for torus sizes at $12\mu m$ than in the near-infrared
The Unified Model torus has been detected only in a handful of AGN

ALMA 432\(\mu\)m view (0.04-0.06” res) of central 2” of NGC1068

• Dust and molecular gas torus (7-10pc). \(M_{\text{GAS}} \approx 10^5\text{M}_\odot\) and \(M_{\text{DUST}} \approx 1600\text{M}_\odot\)

• Circumnuclear disk (300pc x 200pc) with recent SF activity

García-Burillo+2016 and 2018 in prep, also Gallimore+2016, Imanishi+2018
More large tori detected with ALMA

NGC5506

NGC6300

García-Burillo+2018 in prep.
Polar Dust Emission in AGN

- Compact MIR emission (interferometry up to a few pc, imaging up to a few 100pc’s)
- Some AGN show a significant fraction of their MIR emission along the polar direction


Dusty torus model images

Nearly equatorial view

Intermediate view

Nearly polar view

Disappearing torus at low AGN luminosities?

- Torus predicted to disappear at $L_{\text{bol (AGN)}} < 10^{42}\text{erg/s}$: Elitzur & Shlosman 2006

Mason+2012: Mid-infrared emission

Combes+2018, in prep: ALMA 832μm continuum in color + CO(2-1) contours
Inflows/Outflows in NGC1068

Müller-Sánchez+2009: Inflows detected in H$_2$ at 2.12$\mu$m with SINFONI

García-Burillo+2014: Outflows detected in CO(3-2) with ALMA on scales 50pc to 400pc from the AGN. Outflow rate in CND $\sim$ 63 M$_{\odot}$/yr

Gallimore+2016: outflowing torus with ALMA

7pc
A massive “outflowing” torus in NGC5643

Composite ALMA (red) + MUSE (blue, green)

ALMA Integrated CO(2-1)

Massive torus with $M_{\text{gas}} \approx 10^7 M_\odot$ and outflowing in equatorial plane with $v \approx 100 \text{km/s}$

Artist Impression: ESO/M. Kornmesser
An obscured AGN in NGC1377 revealed by a cold molecular gas jet

- No evidence of star formation, therefore outflow must be AGN driven
- Outflow rate 9-40 $M_\odot$/yr
- No continuum dust emission detected at 690GHz (434$\mu$m) with ALMA. Could be explained by an unresolved obscured nuclear source 0.2-0.7 pc?
The new paradigm for the obscuring material of AGN

Pier & Krolik 1992
Schartmann+2008

Wada 2012, 2016
Hönig & Kishimoto 2017

dust
gas

Circinus Galaxy
Hubble Space Telescope • WFC2
Jet-molecular cloud interaction in northern ionization cone: No silicate feature in polarized light: dust grains different from those in ISM?

AGN location <0.3% polarization from the torus
**Porous (large grains) dust:** Li+2008, Smith+2010 (M81 dust produced in AGN wind), Siebenmorgen+2015, Xie+2017

**Different dust species:** Markwick-Kemper+2007

**Radiative transfer effects:** Nikutta+2009

**Modified chemical composition in the presence of a strong radiation field:** Smith+2010, Shi+2014
**Dust composition in quasars**

Example of a QSO fit: corundum: solid red, periclase: dashed red, olivine: solid blue, Mg-rich olivine: dashed blue, PAH: cyan

Mass fractions of various dust species for a sample of 53 quasars ≠ dust composition in ISM

Dust produced in quasar winds? Elvis +2002

Srinivasan+2017, see also Markwick-Kemper+2007, Xie +2017
PAH emission in the nuclear regions of AGN

Jensen+2017

PAH emission excitation on scales of tens of parsecs: AGN vs. Nuclear SF?

Protecting PAHs in the nuclear regions of AGN

PAHs will survive if rate of reaccretion of carbon onto PAHs higher than evaporation rate due to harsh AGN radiation field

\[ \tau \approx 700 \text{ yr} \left( \frac{N_H \text{(tot)}}{10^{22} \text{ cm}^{-2}} \right)^{1.5} \left( \frac{D_{\text{agn}}}{\text{kpc}} \right)^2 \left( \frac{10^{44} \text{ erg s}^{-1}}{L_X} \right) \]


Alonso-Herrero+2014

Torus, nuclear gaseous disks, and/or material in host galaxy provide sufficient material to shield the PAH molecules for Seyfert-like luminosities
Simplest version of the AGN Unified Model

What We Expect to See

Galaxies are oriented randomly in the sky so the disks in their centers should be oriented randomly as well.

Thus we expect to see a random mix of exposed and hidden black holes everywhere we look.

with the obscuring tori having similar properties in all AGN independent of AGN luminosity, redshift, Eddington ratio, etc.
The Obscured AGN fraction

Obscured fraction is usually derived from X-ray column densities ($N_H$) and optical class (type 1 broad vs. type 2 narrow lines)

Dependence with AGN luminosity?

Modelling the AGN IR unresolved emission

Geometrical covering factor (CF) \( f_2 \) is only a function of torus angular width and number of clouds along equatorial direction and defines the fraction of obscured AGN.

\[
N_{LOS}(i) = N_0 e^{-(90-i)^2/\sigma_{torus}^2}
\]

\[
P_{esc} \simeq e^{-N_{LOS}}
\]

\[
\beta = 90-i
\]

\[
f_2 = 1 - \int_0^{\pi/2} P_{esc}(\beta) \cos(\beta) d\beta.
\]
Different torus model parameters for Type 1 and Type 2 AGN

Martínez-Paredes+2017
Also Ramos Almeida+2011, Alonso-Herrero+2011, Mor+2012, Ichikawa+2015
Torus Dust Covering Factors vs Luminosity

- Complete sample of X-ray selected AGN: 132 type 1 AGN and 78 type 2 AGN at redshifts $z \sim 0-1.7$

- Small CF values are preferred at high AGN luminosities, as postulated by simple receding torus models

Seyfert-like luminosities, $42 < L_X < 43.5$

Quasar-like luminosities, $43.5 < L_X < 46$

Type 2 AGN

Type 1 AGN

Type 2 AGN

Type 1 AGN

Mateos+2016, see also Mor+2009, 2012, Roseboom+2015
A non-negligible fraction of luminous, heavily obscured (high covering factors) type-2 AGN X-ray detection (at energies < 10keV) are missing:

Comparison of optical fraction of type 1/type 2 of X-ray selected AGN with the modelled distribution of torus geometrical covering factors
Warm and hot dust deficient quasars are only 10% of type I quasar population.

All quasars have very similar far-infrared SED that are also consistent with those of lower luminosity AGN.

Similar emitting properties in the outer parts of the AGN-heated dusty structures, i.e., optically thin dust in the far-infrared.
Evolution of the obscuring material (torus) in PG quasars

Lyu et al. 2017a

(A) normal quasar

(B) warm-dust-deficient quasar (higher luminosity)

(C) hot-dust-deficient quasar (lower Eddington ratio)

Zhuang et al. 2018

Torus Opening Angle vs. Eddington Ratio

standard disk

torus

slim disk
Summary

We are only starting to glimpse the true nature of the torus and the properties of the AGN dust

- Images of the torus: detailed geometry of the torus in nearby active galaxies including sizes, polar dust
- Inflows/outflows
- Connection with the host galaxy including positive/negative feedback, nuclear star formation activity

- Dust properties in large AGN samples
- Evolution of torus properties in AGN vs luminosity, redshift, Eddington ratio, etc