The search for a disappearing AGN torus

Leonard Burtscher, Richard I. Davies, Ming-yi Lin, Gilles Orban de Xivry, David Rosario, Allan Schnorr-Müller

CO 2.3 µm equivalent width maps

AGN luminosity

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CO 2.3 µm equivalent width maps
What causes AGN activity?
Leonard Burtscher: The MIDI AGN Large Programme

What causes AGN activity?

Variability on „short“ timescales

Novak+ 2011
The AGN „torus“ as resolved on sub-pc scale with VLTI

NGC 1068
Lopez, Jaffe, Burtscher+ 2014

Circinus galaxy
Tristram, Burtscher+ 2013
Disk wind scenario

- Mass outflow $\sim L^{1/2}$; $L \sim \dot{M}_{\text{in}}$
  
  $\rightarrow \dot{M}_{\text{out}}/\dot{M}_{\text{in}} \sim L^{-1/2}$

- since $\dot{M}_{\text{out}}$ must be $< \dot{M}_{\text{in}}$, torus disappears
  at $L_{\text{bol}} \sim 10^{42}$ erg/s (Elitzur & Shlosman 2006)

Radiation-driven outflow / disk wind
(e.g. Gallagher+ 2013)
AGN Torus disappearance

Disk wind scenario

- Mass outflow $\sim L^{1/2}$; $L \sim \dot{M}_{\text{in}}$
  $\rightarrow \dot{M}_{\text{out}}/\dot{M}_{\text{in}} \sim L^{-1/2}$

- since $\dot{M}_{\text{out}}$ must be $< \dot{M}_{\text{in}}$, torus disappears at $L_{\text{bol}} \sim 10^{42}$ erg/s (Elitzur & Shlosman 2006)

Stationary accretion model

- volume filling factor $\Phi \sim \dot{M}_{\text{torus}}^{-1/2} \sim L^{-1/2}$
  $\rightarrow \Phi \sim L^{-1/2}$ (Beckert & Duschl 2004)

- clumpy torus: $\Phi \ll 1$ $\rightarrow$ lower limit for existence of obscuring torus at $L_{\text{bol}} \sim 10^{42}$ erg/s (Hönig & Beckert 2007)
The mid-IR-X-ray relation

D. Lutz et al.: Mid-infrared and hard X-ray emission in AGN

Fig. 5. Hard X-ray luminosities corrected for absorption vs. $6\mu m$ AGN continuum luminosities for those objects where absorption-corrected X-ray flux was available. Symbols are as in Fig. 3. The dotted line indicates slope 1, it is not a fit.

The dispersion is considerable, the ratio for Seyfert 1s varying over an order of magnitude. Ratios for type 2 Seyferts scatter yet wider. This may be partly due to inaccuracies in the absorption correction in the X-ray data. The current data do not allow to determine with certainty whether there is in reality a larger spread for type 2 than for type 1. The two outlying objects Mrk 463 and NGC 6240 are briefly discussed in the Appendix. The spread observed in our sample is significantly larger than in the imaging study of Krabbe et al. (2001), where with the exception of the outlier NGC 6240 other intrinsic hard-X and mid-IR emission varies by just a factor of $3^{-4}$.

This was probably a fortuitous effect of the small sample including $\sim 10$ times less objects than the present study. Given the many factors of AGN spectral energy distribution and geometry relating the hard X-ray flux and the dust reradiation of AGN emission in the mid-infrared, the larger scatter is not surprising. Another significant contribution to the spread is likely due to AGN variability. The X-ray and infrared measurements summarized in Table 1 were usually taken several years apart. Even in case of simultaneous observations, short term variability of the central engine may contribute to the scatter because of different time response and time averaging effects for the X-rays and for the larger scale dust.

3.2. No significant difference between Seyfert 1 and Seyfert 2 types

As surprising results giving here as reasons for the present sample is the failure to detect the difference between type 1 and type 2 Seyferts that is predicted by the most straightforward versions of unified models. The median $\log \left( \frac{F(2-10 keV)}{\nu F(6 \mu m)} \right)$ is $-0.41$ for type 1 objects and $-0.63$ for type 2. This would not change strongly replacing the few lower limits by detections (Fig. 6). The key point is not the small difference found, which might even be reduced slightly if some of the Sy 2 limits were replaced by detections or with full correction for stellar continuum, it is the failure to detect a strong and significant difference in the opposite direction. If the mid-infrared continuum in Seyfert 2s is suppressed by a factor of $\sim 8$ (Clavel et al. 2000), the hard/IR ratio should be higher by the same factor compared to Seyfert 1s. While our targets are from a heterogeneous set of ISO observing programs, they do not represent a preselection by mid-IR flux which may affect such a comparison. The main observing programs involved did not invoke such a selection. A major part, e.g., is formed by objects from the CfA sample (Huchra & Burg 1992). Also, for example, most AGNs from the hard X-ray selected sample of Piccinotti et al. (1982) are included. As discussed by Maiolino & Rieke (1995), samples like the CfA one may be biased against obscured objects and thus not reproduce the real fractions of Seyfert types. Our analysis normalizing to intrinsic X-rays should be robust to such effects as long as reaching lower but still significant numbers of obscured systems. In unified schemes (e.g. Antonucci et al. 1993), the difference between Seyfert types is due to effects of viewing intrinsically similar objects from different directions, because an anisotropic distribution of absorbing material (e.g. the "torus") absorbs, scatters, and reprocesses the direct AGN light. In the most simple version, a central very small source (also emitting $L_{bol} \sim 10^{42}$ erg/s
The mid-IR-X-ray relation

Even with sensitive mid-IR observations it is hard to push below this limit
Probing the non-stellar continuum with SINFONI

Figure 1. Azimuthal average of the CO equivalent width. Significant dilution is seen in only three galaxies, all Seyferts. The triangles are Seyfert galaxies while the circles are quiescent galaxies, and all curves are labeled according to those defined in Table 1. The horizontal dashed line represents the lower bound on an undiluted CO bandhead equivalent width (see Section 2.3 for details). A typical error bar, representative of the standard deviation of the equivalent width of all pixels at each annulus, is shown on the right.

(A color version of this figure is available in the online journal.)

Figure 2. Maps of non-stellar continuum in three galaxies (NGC 3227, NGC 6300, and NGC 6814) where significant dilution of the CO bandheads is seen due to an AGN continuum. The central circle represents the radius at which the dilution factor is 2. In all maps north is up and east is to the left.

(A color version of this figure is available in the online journal.)

3. CHARACTERIZATION OF NUCLEAR MOLECULAR GAS AND STARS

3.1. 2D Distribution and Kinematics

In all 10 galaxies the first two CO bandheads at $\lambda 2.2935, 2.3226 \mu m$ are detected well enough to reliably measure the velocity and velocity dispersion across a large fraction of the 8″ × 8″ FOV. H$_2$1–0 S(1) $\lambda 2.1218 \mu m$ emission is detected in seven of the galaxies, with all three of those with non-detections being quiescent galaxies. Two of these non-detections are galaxies for which Martini et al. (2003a) find no detectable nuclear dust structure, which is known to correlate with low molecular gas content (e.g., Young & Scoville 1991; Dumase et al. 2010). Spectra of each galaxy integrated over the measured FOV are shown in Figure 3.

The 2D flux distribution, velocity, and velocity dispersion ($\sigma$) of the stellar and gas kinematics have been extracted by fitting the CO bandheads and H$_2$ emission, respectively. Before extraction of the kinematics the data cubes were spatially binned to a minimum signal-to-noise ratio (S/N) with the Voronoi

Hicks+ 2013
Probing the non-stellar continuum with SINFONI
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![Graphs and diagrams showing non-stellar continuum in galaxies](Images)
Probing the non-stellar continuum with SINFONI

NGC 2110 1" off nucleus

EW~10Å

NGC 2110 nucleus

EW~1Å

Davies+ 2007

Hicks+ 2013
Probing the non-stellar continuum with SINFONI

NGC 2110 1" off nucleus

EW~10Å

NGC 2110 nucleus

EW~1Å

Davies+ 2007

W_Co 2-0 2.29 μm

Age [yrs]

10^7 10^8 10^9 10^10

LLAGNs inactive

Seyferts

Typical Error

Hicks+ 2013
NGC 3281 (AGN)

box: 3" (700 pc)  CO EW [Å]
NGC 4030 (inactive)

box: 8'' (900 pc)

CO EW [Å]
NGC 1097 (LINER)

box: 3“ (400 pc)  CO EW [Å]
NGC 2911 (LINER)

no dilution, but two stellar populations
NGC 5135 (Seyfert 2)

some dilution and two spiral arms

box: 8" (2 kpc)  CO EW [Å]
Equivalent Width (r)

- $r < 200$ pc
- $r > 200$ pc
Equivalent Width ($r$)

- $r < 200$ pc
- $r > 200$ pc

No bimodality

Intrinsic distribution
Equivalent Width ($r$)

- Intrinsic distribution: no bimodality
- Gray shaded: with proper X-ray measurements

$r < 200$ pc
$r > 200$ pc
Equivalent Width ($r$)

- Nuclear distribution: bimodality
- Intrinsic distribution: no bimodality

$r < 200$ pc
$r > 200$ pc
The EW distribution

\[ EW_{\text{obs}} = \frac{EW_{\text{int}} \cdot L_{\text{stars}} + \left( \frac{EW_{\text{dilute}} \cdot L_{\text{dilute}}}{L_{\text{stars}} + L_{\text{dilute}}} \right)}{L_{\text{stars}} + L_{\text{dilute}}} = \frac{EW_{\text{int}}}{1 + \frac{L_{\text{dilute}}}{L_{\text{stars}}}} \]
The EW distribution

\[ EW_{\text{obs}} = \frac{E W_{\text{int}} \cdot L_{\text{stars}} + \underbrace{E W_{\text{dilute}}} \cdot L_{\text{dilute}} = \frac{E W_{\text{int}}}{1 + \frac{L_{\text{dilute}}}{L_{\text{stars}}}} }{L_{\text{stars}} + L_{\text{dilute}}} \]

expected

observed
The EW distribution

\[
EW_{\text{obs}} = \frac{EW_{\text{int}} \cdot L_{\text{stars}} + EW_{\text{dilute}} \cdot L_{\text{dilute}}}{L_{\text{stars}} + L_{\text{dilute}}} = \frac{EW_{\text{int}}}{1 + \frac{L_{\text{dilute}}}{L_{\text{stars}}}}
\]
The EW distribution

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**Expected**

**Observed**
The EW distribution

\[
EW_{\text{obs}} = \frac{EW_{\text{int}} \cdot L_{\text{stars}} + EW_{\text{dilute}} \cdot L_{\text{dilute}}}{L_{\text{stars}} + L_{\text{dilute}}} = \frac{EW_{\text{int}}}{1 + \frac{L_{\text{dilute}}}{L_{\text{stars}}}}
\]

KS test:
\[d = 0.1 \text{ Å},\]
\[p = 0.985\]
\((\sim 2.5 \sigma)\)
$L_{\text{dilute}}$ vs. $L_X$

- BAT AGNs

![Graph showing the relationship between $L_{\text{dilute}}$ and $L_X$.](image-url)
$L_{\text{dilute}}$ vs. $L_X$

- BAT AGNs
- 2-10 keV / $L_{\text{dilute}}$ limits
$L_{dilute}$ vs. $L_X$

$L_{bol} \sim 10^{42} \text{ erg/s}$

- BAT AGNs
- 2-10 keV / $L_{dilute}$ limits
L_{dilute} vs. L_X

$L_{bol} \sim 10^{42} \text{ erg/s}$

- Good correlation between non-stellar K-band light and X-ray light.
- Torus does not disappear above $L_{bol} \sim 10^{42} \text{ erg/s}$.

2-10 keV / $L_{dilute}$ limits

**BAT AGNs**
Good correlation between non-stellar K-band light and X-ray light. Torus does not disappear above $L_{\text{bol}} \sim 10^{42}$ erg/s.
Dilute vs. LX

- BAT AGNs
- 2-10 keV / \( L_{dilute} \) limits
- Compton-thick sources

Need ~ 10x better spatial resolution to discriminate between stellar and non-stellar light in very weak AGNs...

Good correlation between non-stellar K-band light and X-ray light. Torus does not disappear above \( L_{bol} \sim 10^{42} \) erg/s.
Stellar luminosity

Histogram Density

log L(stars) / [erg/s]
Stellar luminosity
Stellar luminosity
NGC 1097

Davies+ 2007, 2009
A near-IR – mid-IR correlation

- Tight correlation between near-IR non-stellar light and mid-IR
- No type 1/2 dichotomy (see also Lutz+, Gandhi+, Horst+, Asmus+, ...)
- But: perhaps some interesting outliers
Conclusions + Outlook

• The bimodality in the dilution of starlight by the AGN is caused by a nearly constant stellar surface brightness and a wide range of AGN luminosities.

• We establish a new correlation between non-stellar continuum in the K band and X-ray luminosity. Outliers have peculiar X-ray properties.

• We also find a good correlation between the nuclear non-stellar near-IR light and the nuclear mid-infrared light. Some of the few outliers are known to be devoid of hot dust.
Backup slides
Powerful AGN sample
ongoing SINFONI + XSHOOTER observations

![Graph showing the relationship between log(L(14-195 keV)/erg s^-1) and redshift.](image)
Nuclear Starburst in NGC1068

H-band non-stellar continuum

H-band stellar continuum

stellar velocity (km/s)

stellar dispersion (km/s)

Davies+ 07
Star forming Region Size & Mass

fit intensity & dispersion simultaneously with bulge + ‘disk’

- for each component, fit: $R_{\text{eff}}, n, I_0, \sigma$

- bulge component
  
  $R_{\text{eff}}$ & $n$ similar to NICMOS profile

- nuclear ‘disk’ component
  
  $R_{\text{eff}} = 0.51'' = 36\text{pc}$
  
  $n = 1.6$
  
  $\sigma = 35-55\text{km/s}$

- $M_{\text{dyn}} = 5-9\times10^7M_{\text{sun}}$

- $M_{\text{BH}} \sim 1\times10^7M_{\text{sun}}$ (Greenhill+ 96)

- $\Sigma_{\text{dyn}} \sim 2\times10^4 \text{M}_{\text{sun}}/\text{pc}^2$

- $M_{\text{dyn}}/L_K \sim 4$ agrees with starburst age 200-300Myr (Davies+ 07)

- $M_{\text{BH}}/M_{\text{stars}} \sim 0.15$
Nuclear Starburst in NGC1097

Davies+ 07, 09

K-band non-stellar continuum

K-band stellar continuum

stellar velocity (km/s)

stellar dispersion (km/s)
Star forming Region Size & Mass

fit intensity & dispersion simultaneously with bulge + ‘disk’

- for each component, fit: $R_{eff}$, $n$, $I_0$, $\sigma$
- bulge component
  $R_{eff}$ & $n$ similar to NACO profile (Prieto+05)
- nuclear ‘disk’ component
  $R_{eff} = 0.28'' = 24$pc $n = 0.8$
  $\sigma <\sim 30$ km/s
- $M_{dyn} = 1-5\times10^7M_{sun}$
- $M_{BH}$
  $12\times10^7M_{sun}$ (Lewis+ 06, $\sigma=196$km/s)
  $5\times10^7M_{sun}$ (using $\sigma=155$km/s)
- low stellar mass, consistent with young age ($M_{dyn}/L_K < 1$)
- $M_{BH}/M_{stars} > 1$