The Role of Molecular Hydrogen in Obscuring AGN

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AGN Unification Model: the 'Torus'

Obscuring medium is optically & geometrically thick.

- Warped disk traced by masers on scales of < 1 pc
- IR interferometric techniques reveal thermal emission on a scale < 10 pc
- Models of clumpy tori suggest they extend out to scales of 10-60 pc
- X-ray observations indicate the column density (at least on the small scales measured) is $10^{22-24}$ cm$^{-2}$, i.e. optically thick
Motivation for Characterizing Nuclear H$_2$

- H$_2$ traces the cooler, and presumably more extended, gas in the nuclear region.
- Relationship between H$_2$ and the nuclear star formation (Davies et al. 2007).
- H$_2$ contribution to obscuring & fueling of the AGN.

Little is known about molecular hydrogen within the central 100pc of AGN, especially in Seyfert 1 galaxies.
Measurements of the Central 100pc: Distribution & Kinematics

- High spatial resolution
  - Adaptive optics with AGN as the AO reference
  - $K$-band minimizes the AGN emission and for local AGN contains the $H_2$ 1-0 S(1) 2.1218 $\mu$m emission line

- 2-D Kinematics: integral field spectrometers
  - SINFONI on VLT UT4
  - OSIRIS on Keck II
Measurements of the Central 100pc: Distribution & Kinematics

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- 2-D Kinematics: integral field spectrometers
  - SINFONI on VLT UT4
  - OSIRIS on Keck II
# The Sample of Observed AGN

<table>
<thead>
<tr>
<th>Object</th>
<th>Classification</th>
<th>D (Mpc)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1097</td>
<td>Sy 1 / LINER</td>
<td>18</td>
<td>0.25&quot;</td>
</tr>
<tr>
<td>NGC 3227</td>
<td>Sy 1</td>
<td>17</td>
<td>0.07&quot;</td>
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<tr>
<td>NGC 3783</td>
<td>Sy 1</td>
<td>42</td>
<td>0.18&quot;</td>
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<tr>
<td>NGC 4593</td>
<td>Sy 1</td>
<td>36</td>
<td>0.08&quot;</td>
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<tr>
<td>NGC 7469</td>
<td>Sy 1</td>
<td>66</td>
<td>0.06&quot;</td>
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<tr>
<td>NGC 1068</td>
<td>Sy 2</td>
<td>14</td>
<td>0.09&quot;</td>
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<tr>
<td>Circinus</td>
<td>Sy 2</td>
<td>4</td>
<td>0.22&quot;</td>
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**SINFONI Data**

<table>
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<tr>
<th>Object</th>
<th>Classification</th>
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<tr>
<td>NGC 3227</td>
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<td>17</td>
<td>0.07&quot;</td>
</tr>
<tr>
<td>NGC 4051</td>
<td>Sy 1</td>
<td>9</td>
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<td>NGC 4151</td>
<td>Sy 1</td>
<td>13</td>
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<td>NGC 6814</td>
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<td>21</td>
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<tr>
<td>NGC 7469</td>
<td>Sy 1</td>
<td>66</td>
<td>0.06&quot;</td>
</tr>
</tbody>
</table>

**OSIRIS Data**

Mean Resolution: 20 pc
3D Near-IR Data: AGN, Stellar, & $H_2$ Emission
3D Near-IR Data: Flux, Velocity, & Dispersion

Flux       Velocity (v)       Vel. Disp. (σ)

NGC 1097

Flux       Velocity (v)       Vel. Disp. (σ)

Circinus

Flux       Velocity (v)       Vel. Disp. (σ)

NGC 3227

Flux       Velocity (v)       Vel. Disp. (σ)

NGC 3783

Flux       Velocity (v)       Vel. Disp. (σ)

NGC 4151

Flux       Velocity (v)       Vel. Disp. (σ)

NGC 7469

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Properties of the Nuclear Molecular Hydrogen

- **Size Scale**
- **2D Velocity Field**
- **Velocity Dispersion**
- **Dynamical Mass**
- **Column Density**
**Size Scale**
- HWHM < 35 pc
- Disk-like profile

**2D Velocity Field**

**Velocity Dispersion**

**Dynamical Mass**

**Column Density**

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HWHM of radial average is less than 35 pc

Sérsic fits suggest disk-like distributions

\[ n = 1.6 \pm 0.4 \text{ on average} \]
Size Scale
- HWHM < 35 pc
- Disk-like profile

2D Velocity Field
- Disk rotation down to ~20 pc

Velocity Dispersion

Dynamical Mass

Column Density

Ordered velocity field suggests disk rotation
No evidence of a warp down to smallest scales measured

Best fit PA and inclination angle determined using kinemetry.
(Krajnović et al. 2006)
Size Scale
- HWHM < 35 pc
- Disk-like profile

2D Velocity Field
- Disk rotation down to ~20 pc

Velocity Dispersion

Dynamical Mass

Column Density
- Consistent with larger scale disk rotation (ISAAC)
- Consistent with rotation of cold molecular gas (e.g. CO 2-1; Schinnerer et al. 2000a,b & Davies et al. 2004)
**Size Scale**
- HWHM < 35 pc
- Disk-like profile

**2D Velocity Field**
- Disk rotation
down to ~20 pc

**Velocity Dispersion**
- High $\sigma$ implies bulk motion, i.e. thick disk
- Average $v_{\text{rot}}/\sigma = 0.9 \pm 0.3$ at 30 pc
- Random motions significant w.r.t. $v_{\text{rotation}}$

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**Velocity & Dispersion (km s$^{-1}$)**

- $v$ and $\sigma$ vs. $r$ (arcsec)
- Flux vs. $r$
- PSF vs. $r$

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**Size Scale**
- HWHM < 35 pc
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**2D Velocity Field**
- Disk rotation down to ~20 pc

**Velocity Dispersion**
- \( \frac{v_{\text{rot}}}{\sigma} < 1 \)
- High \( \sigma \) implies bulk motion, i.e. thick disk
- Average \( \frac{v_{\text{rot}}}{\sigma} = 0.9 \pm 0.3 \) at 30 pc
- Random motions significant w.r.t. \( v_{\text{rotation}} \)

**Dynamical Mass**

**Column Density**

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**Size Scale**
- HWHM < 35 pc
- Disk-like profile

**2D Velocity Field**
- Disk rotation
  down to ~20 pc

**Velocity Dispersion**
- $v_{rot}/\sigma < 1$

**Dynamical Mass**

**Column Density**

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**Velocity Dispersion**

- Elevated dispersion is confirmed with ISAAC data outer disk $\sigma \sim 45$ km s$^{-1}$
- H$_2$ excitation via 20-40 km s$^{-1}$ shocks

![Graph showing velocity dispersion and dynamical mass](image.png)

**NGC 3227**

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**Size Scale**
- HWHM < 35 pc
- Disk-like profile

**2D Velocity Field**
- Disk rotation down to ~20 pc

**Velocity Dispersion**
- $v_{\text{rot}}/\sigma < 1$
- $z_0/r = 1.3 \pm 0.2$

**Dynamical Mass**

**Column Density**

---

**Estimated Disk Height**

- Elevated dispersion is confirmed with ISAAC data outer disk $\sigma \sim 45$ km s$^{-1}$
  - $\text{H}_2$ excitation via 20-40 km s$^{-1}$ shocks
  - Higher $\sigma$ possible with bow shocks
    - e.g. Orion bullets, HH99B have 80-120 km s$^{-1}$ oblique shocks

- Disk Height:
  $$z_0 = \frac{\sigma^2}{2\pi G \Sigma}$$
  $$z_0 = r \left(\frac{\sigma}{v_{\text{rot}}}\right)$$

- On average:
  $$z_0/r (30\text{pc}) = 1.3 \pm 0.2$$

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- $v_{\text{rot}}/\sigma < 1$
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**Dynamical Mass**
- account for $\sigma$
- $M_{\text{dyn}} \sim 10^8 M_\odot$

**Column Density**

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**Dynamic mass estimate must account for the significant velocity dispersion:**

\[
M_{\text{dyn}} = \frac{(v_{\text{rot}}^2 + 3\sigma^2) R}{G}
\]

- Average $M_{\text{dyn}} (30\text{pc}) = (1.0 \pm 0.7) \times 10^8 M_\odot$

Erin K. S. Hicks – June 2008 – ESO 3D
**Size Scale**
- HWHM < 35 pc
- Disk-like profile

**2D Velocity Field**
- Disk rotation down to ~20 pc

**Velocity Dispersion**
- $v_{rot}/\sigma < 1$
- $z_o/r = 1.3 \pm 0.2$

**Dynamical Mass**
- account for $\sigma$
- $M_{dyn} \sim 10^8 M_\odot$

**Column Density**

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**Estimated Column Density**

$$M_{gas} = M_{dyn} \times f_{gas}$$

**Estimating $f_{gas}$:**
1. SBs and ULIRGs 10-20 %
2. $L_{CO \ 2-1} \rightarrow M_{H2}$ 10-60 %
3. $L_{H2} \rightarrow M_{gas}$ 8-90%
4. Kennicutt-Schmidt Law $\Sigma_{SFR} \rightarrow \Sigma_{gas}$ 24-90 %

**Assuming $f_{gas} > 10\%$ gives a lower limit on $N_H$**

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- \( \frac{v_{\text{rot}}}{\sigma} < 1 \)
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**Dynamical Mass**
- account for \( \sigma \)
- \( M_{\text{dyn}} \sim 10^8 M_\odot \)

**Column Density**
- \( N_H > 10^{23} \text{ cm}^{-2} \)

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**Estimated Column Density**

\( N_H \) is at least \( 10^{23} \text{ cm}^{-2} \), which is enough to obscure an AGN
Properties of the Nuclear Molecular Hydrogen

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- **Velocity Dispersion**
  - $v_{\text{rot}}/\sigma < 1$
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- **Dynamical Mass**
  - account for $\sigma$
  - $M_{\text{dyn}} \sim 10^8 M_{\odot}$

- **Column Density**
  - $N_H > 10^{23} \text{ cm}^{-2}$

The molecular gas on scales of ~10 pc is in a geometrically and optically thick disk.

This gas is likely to be associated with (the global structure of) the obscuring 'torus'.

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Nuclear Stellar Disks

- Similar spatial scales, with a HWHM stellar light distribution of ~ 50pc
- Evidence of stellar nuclear disks
- H$_2$ and stellar kinematics are very similar

Davies et al. 2007
Nuclear Stellar Disks

- Similar spatial scales, with a HWHM stellar light distribution of ~50 pc
- Evidence of stellar nuclear disks
- $\text{H}_2$ and stellar kinematics are very similar
Similar spatial scales, with a HWHM stellar light distribution of ~ 50pc

Evidence of stellar nuclear disks

H$_2$ and stellar kinematics are very similar

NGC 1097: comparison of stars and H$_2$
Nuclear Stellar Disks

- Similar spatial scales, with a HWHM stellar light distribution of ~ 50pc
- Evidence of stellar nuclear disks
- H$_2$ and stellar kinematics are very similar

NGC 1097: comparison of stars and H$_2$

gas and stars are spatially mixed in a thick disk
Velocity Dispersion Correlates with SFR

<\text{SFR}> from Davies et al. 2007

Linear Correlation Coefficients > 0.7
Kennicutt-Schmidt Law in the Central 100pc of AGN

\[ \log \Sigma_{\text{SFR}} \left( M_{\text{Sun}} \, \text{yr}^{-1} \, \text{kpc}^{-2} \right) \]

\[ \log \Sigma_{\text{gas}} \left( M_{\text{Sun}} \, \text{pc}^{-2} \right) \]

\[ f_{\text{gas}} \]

NGC3227
NGC1068
NGC1097
NGC7469
NGC3783
Circinus
KS Low 1998
KS Low 2007

Erin K. S. Hicks – June 2008 – ESO 3D
Energy must be injected into the system in order to maintain the bulk rotation of the H$_2$ clouds.

- **Radial out/in flow** (e.g. Elitzure & Shlosman 2006) **No kinematic evidence**
- **Disk warp** (Nayakshin 2005, Caproni et al. 2006) **No kinematic evidence**
- **Supernovae** (Wada & Norman 2002) **SNR 1-4 orders of magnitude too low** (Davies et al. 2007)
- **Stellar winds** (Nayakshin & Cuadra 2007) **Only able to achieve z$_0$ ~ few pc**
- **Radiation pressure from the AGN** (Krolic 2007) **Only able to achieve z$_0$ ~ few pc**
  - **Radiation pressure from the stars** (Thompson et al. 2005) **Able to achieve z$_0$ ~ 10s pc**

Stellar radiation pressure is the most likely mechanism, although supernovae, stellar winds, and AGN radiation pressure can contribute.
Speculation on Gas, Star Formation, and Fueling of AGN

- intense starbursts occur in the central 10s of pc around AGN
- intensity of the nuclear starburst likely depends on inflow rate to this region
- velocity dispersion of gas depends on starburst intensity via radiation pressure

low starburst intensity → low gas dispersion → no thickening → no torus
intense starburst → high gas dispersion → thickened central region → torus

Both scenarios can fuel an AGN
The Role of Nuclear $\text{H}_2$ and SB in Obscuring AGN

Typical properties for the observed AGN:

- HWHM $\leq$ 35 pc
- Sersic $n = 1.6 \pm 0.4$
- $v_{\text{rot}}/\sigma = 0.9 \pm 0.3$
- $z_o/r = 1.3 \pm 0.2$
- $M_{\text{dyn}} = (1.0 \pm 0.7) \times 10^8 \, M_\odot$
- $n_H > 10^{23} \, \text{cm}^{-2}$

At a radius of 30 pc

The obscuring medium on scales of 10s pc is a dynamic structure with a greater fraction of lines of sight obscured with increasing rates of star formation.

In such a case, the Seyfert 1 vs. Seyfert 2 properties of an AGN would depend on the state of the nuclear starburst.