A Connection between AGN Activity and Nuclear Star Formation in Seyfert Galaxies

R. Davies¹, R. Genzel¹, L. Tacconi¹, E. Hicks¹, F. Mueller Sánchez¹, S. Friedrich¹, A. Sternberg²

¹ Max Planck Institute for Extraterrestrial Physics
² University of Tel Aviv, Israel

- black hole mass from stellar dynamics to test reverberation masses (BLR geometry) & $M_{BH}-\sigma$ relation
- distribution & kinematics of molecular gas, and relation to obscuring material
- extent, intensity, & history of recent star formation and relation to AGN
## Adaptive Optics Observations of AGN with Keck & VLT

<table>
<thead>
<tr>
<th>object</th>
<th>type</th>
<th>Mpc</th>
<th>resolution</th>
<th>ApJ,</th>
<th>IRAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mkn 231</td>
<td>ULIRG, Sy1, QSO</td>
<td>170</td>
<td>0.176”</td>
<td>613, 78</td>
<td></td>
</tr>
<tr>
<td>05189-2524</td>
<td>ULIRG, Sy1</td>
<td>170</td>
<td>0.12”</td>
<td>100pc</td>
<td></td>
</tr>
<tr>
<td>NGC 2992</td>
<td>Sy1</td>
<td>33</td>
<td>0.30”</td>
<td>48pc</td>
<td>Friedrich+</td>
</tr>
<tr>
<td>NGC 3783</td>
<td>Sy1</td>
<td>42</td>
<td>0.18”</td>
<td>37pc</td>
<td></td>
</tr>
<tr>
<td>NGC 7469</td>
<td>Sy1</td>
<td>66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 3227</td>
<td>Sy1</td>
<td>17</td>
<td>0.085”</td>
<td>7pc</td>
<td>ApJ, 646,754</td>
</tr>
<tr>
<td>NGC 1097</td>
<td>LINER, Sy1</td>
<td>18</td>
<td>0.245”</td>
<td>21pc</td>
<td></td>
</tr>
<tr>
<td>NGC 1068</td>
<td>Sy2</td>
<td>14</td>
<td>0.085”</td>
<td>6pc</td>
<td>Mueller Sanchez+</td>
</tr>
<tr>
<td>Circinus</td>
<td>Sy2</td>
<td>4</td>
<td>0.22”</td>
<td>4pc</td>
<td>A&amp;A, 454,481</td>
</tr>
</tbody>
</table>

**star formation:** Davies+ (astroph 0704.1374)  
**molecular gas:** Hicks+ in prep
examples of SINFONI data

NGC 3227  NGC 2992  NGC 1097  NGC 3783  NGC 1068

non-stellar
H/K continuum

stellar
H/K continuum

H$_2$ 1–0S(1) emission line

0.9”  3.7”  4.2”  3.5”  4.7”
NGC1068: fuelling in action

85mas (6pc) resolution

\[ \text{H}_2 \text{ flux} \]

\[ \text{H}_2 \text{ velocity} \]

Mueller Sanchez+ in prep

55pc
CO equivalent width: stellar vs non-stellar continuum

It is possible to correct for dilution by AGN & estimate stellar continuum without knowing anything about the stellar population

STARS stellar cluster models
$W_{\text{CO6-3}} \sim 4.5\text{Å}$ & $W_{\text{CO2-0}} \sim 12\text{Å}$

adapted from Oliva et al. 1995
Stellar Bolometric Luminosity

For the stellar continuum, it is possible to estimate $L_{\text{bol}}$ from $L_K$ to within a factor of 3 without knowing anything about the star formation history.

Estimating stellar bolometric luminosity is simple and robust.

STARS stellar cluster models
**Star Formation Diagnostics**

**Bry equivalent width**
- correct Bry for AGN contribution (e.g. NLR, jet) through morphology & kinematics
- ratio to *stellar* continuum

**mass-to-light ratio**
- use spatially resolved kinematics ($V_{\text{rot}}$ & $\sigma$) to estimate dynamical mass
- correct $L_K$ for non-stellar continuum
- gives upper limit to $M/L_K$ for most recent star formation

**radio continuum (supernova rate)**
- resolved continuum with low $T_B$ probably star formation
- correct flux for unresolved point source associated with AGN, and also for any jet contribution
- estimate supernova rate

---

**NGC1068**

**Bry equivalent width**

- [Image of NGC1068 with Bry equivalent width map]

**NGC1068**

**Bry equivalent width**

- [Image of NGC1068 with Bry equivalent width map]

**Mkn 231**

- [Image of Mkn 231 with contour map]

- [Image of Mkn 231 with contour map]

**Carilli et al. (1998)**

- 0.06” beam
- source size 0.44×0.31”
nuclear stellar continuum resolved in all cases

age is 10-300 Myr

but low $W_{\text{Br}\gamma}$ means star formation is no longer active

Cid Fernandes+ 04: central ~200pc of 79 nearby Seyfert 2s; 1/3-1/2 have experienced significant star formation in last few hundred Myr
Star Formation occurs in Nuclear Disks

- **nuclear disk in NGC1068:**
  - detected to $\sim 70$ pc
  - mass $\sim 1.2 \times 10^8 \, M_{\odot}$
  - scale height $\sim 6$ pc

Kinematic evidence ($\sigma$-drops) for nuclear disks is seen in $\sim 30\%$ of spiral galaxies (Ganda+06, Emsellem 07)
Are Nuclear Disks related to Nuclear Clusters?

Nuclear Clusters seen with HST in 70%-90% of all galaxies, with sizes 2-60pc (Carollo+98, Böker+02, Graham+03, Lotz+04, Grant+05, Ferrarese+07)

ages 10Myr to 10Gyr, masses $10^5 - 10^8 M_{\odot}$ (Walcher+05,06 Rossa+06)

![Graph showing the relationship between the radius of galaxies and their relative intensity, with a marked radius of ~40pc for NGC 1097.](image)
Stellar Bolometric Luminosity

Starbursts are close to being Eddington limited

e.g. M51 star clusters and Arp 220 (Scoville 03)
e.g. radiatively supported starburst models (Thompson et al. 05)

Note: $500L_{\odot}/M_{\odot} \sim 10^{13}L_{\odot}/\text{kpc}^2$ for $\Sigma=2\times10^4M_{\odot}/\text{pc}^2$
What does it take for a starburst to be Eddington limited?

If gas is present at the beginning, then star formation time scale must be of order ~10Myr. This is consistent with the star forming timescales implied by the data.
How much higher was the stellar luminosity?

STARS illustrative stellar cluster model: for recent star formation which is no longer active, the luminosity was of order 10 times higher in the past.

exponentially decaying star formation rate, $\tau_{SF}=10\,\text{Myr}$

normalisation set by $L_{\text{bol}} = 2 \times 10^9 L_{\odot}$ at $100\,\text{Myr}$

B$\gamma$ flux drops rapidly

$L_K$ similar to $L_{\text{bol}}$
Why should the Star Formation Rate be so High?

Nuclear starbursts lie on the Kennicutt Schmidt law

\[ \Sigma_{\text{SFR}} = 2.5 \times 10^{-4} \Sigma_{\text{gas}}^{1.4} \]

when SFR is time averaged and 30% of dynamical mass is attributed to gas.

SFR is high because the gas surface mass density is high. As a result the star forming efficiency is also high.
Why should the Star Formation Rate be so High?

Wang et al. 2007

‘Galaxies in Zone III are undergoing suppressed star formation’
A Scenario for Star Formation around AGN

- Gas accumulates in central 100pc
- Region cannot form stars due to high turbulence (Toomre criterion, $Q=\sigma_\kappa/\pi G\Sigma$) [Erin Hicks, short talk]
- Eventually, the high gas density leads to a high star formation rate
- Starburst is Eddington limited, generating a huge radiation pressure
- Because the efficiency is high, the starburst is short lived
- Starburst fades and is then dormant until gas is replenished

... but how is star formation related to the torus & the AGN?
Relation of Star Formation to Molecular Gas

(Erin Hicks, short talk)

in general, gas
- is centrally concentrated
- has high dispersion (vertically extended)
- has high column density
these are the properties of an obscuring torus

kinematics of stars & gas are similar at r<0.5"
i.e. gas & stars are mixed
in general, gas
- is centrally concentrated
- has high dispersion (vertically extended)
- has high column density

these are the properties of an obscuring torus

kinematics of stars & gas are similar at r<0.5”

i.e. gas & stars are mixed
in general, gas
- is centrally concentrated
- has high dispersion (vertically extended)
- has high column density
these are the properties of an obscuring torus

kinematics of stars & gas are similar at $r<0.5''$
i.e. gas & stars are mixed
Starburst - AGN connection

Delay of 50-100 Myr between starburst & AGN activity

best estimate of time since most recent star forming episode began
Starburst - AGN connection

What role do stellar ejecta play in fuelling the black hole?

**OB stars**
- significant mass loss, but at speeds of ~1000km/s and only for a short time;
- in Galactic Centre, winds are partially responsible for stopping accretion (Ozernoy+96,97, Cuadra+06)

**supernovae**
- ~$10^6$ SNe, each ejecting ~$5M_{\text{sun}}$ at ~5000km/s;
- most likely outcome is a superwind rather than accretion

SNe occur at starburst ages of 10-50Myr, and probably play a role in delaying the fuelling of the black hole.

STARS illustrative stellar cluster model
Starburst - AGN connection

What role do stellar ejecta play in fuelling the black hole?

AGB stars stars of 1-8$M_{\text{sun}}$ reach AGB phase after $\sim$50Myr; winds have speeds of 10-30km/s and remain bound; mass available $>0.02M_{\text{sun}}/\text{yr}$ over timescale of 50-200Myr; total mass $\sim 2 \times 10^7M_{\text{sun}}$ over 1Gyr

---

**mass lost in stellar ejecta**

- Mass loss rate ($M_{\text{sun}}$ yr$^{-1}$)
- Age [yrs]

**mass available to accrete onto BH**

- Accretion rate ($M_{\text{sun}}$ yr$^{-1}$)
- Age [yrs]

STARS illustrative stellar cluster model
Summary

• adaptive optics integral field spectroscopy of AGN, with spatial resolution to better than 10pc

• detailed morphologies & kinematics of molecular gas and stars

• star formation:
  - recent, intense, short lived starbursts in central few 10s of pc
  - stars & gas are mixed - starburst occurs in the molecular torus
  - delay between starburst activity & AGN activity
  - AGN accretion probably delayed by supernovae and fuelled by winds from AGB stars