Molecular tori, BH fueling & feedback in nearby AGN

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Outline

➔ Angular momentum transfer
➔ Dynamical features: nuclear bars & spirals

➔ Fueling due to gravity torques
➔ Feedback, outflows (SF, AGN)

➔ Molecular tori
➔ Decoupling, different orientations
Main features of barred galaxies

Gas tends to follow periodic orbits
Dissipation, cloud collisions
→ tilt of the ellipses
→ spiral arms

The spiral is open
Rotation of 180-360°
Sanders & Huntley 1976,
Contopoulos, 1980, Athanassoula 1992
Embedded structures

Bars exert a torque on the gas \( \Rightarrow \) gas piles up and stalls in a nuclear ring

**Decoupling of a secondary bar**

In between the two ILR:
perpendicular orbits \( x2 \)
Do not sustain the bar anymore

New faster bar inside the ILR ring
+ weakening of the bar, z-resonance
Peanut-shape bulge

Friedli 1993

stars

gas

Friedli 1993
Torques exerted on the gas by the bar

Torques change sign at each resonance

Inside CR, gas loses angular momentum, **infalls towards the centre**
Outside CR, on the contrary, gas **accumulates at OLR**
Fueling: Bar gravity torques

Torques computed from the HST red image, on the gas distribution.

Torque map for NGC 3627
(Casasola et al 2011)
Contours = gas density

Correlation between bars and AGN
Statistics -- Time-scales
10-100pc fueling

⇒ Only ~35% of negative torques in the center, About 20 galaxies (Garcia-Burillo & Combes 2012)

⇒ Rest of the times, positive torques, gas stalled in ring

⇒ Fueling phases are short, a few $10^7$ yrs (feedback)

⇒ Star formation fueled by the torques, always associated to AGN activity, but with longer time-scales
NGC 6951: no gas in the center

Van der Laan 2011
Small-scale accretion

Simulations of gas accretion onto a central BH $\rightarrow$ thick disks ($\sim 10$ pc)

Zoomed simulation: cascade of $m=2$, $m=1$, + clumps and turbulence

When $f_{\text{gas}}$ large

$10^{22}-10^{25}$ cm$^{-2}$

Clump unstable

Warps, twists

Bending

$\rightarrow$ Thick disks

$\rightarrow$ Dynamical friction of GMC

If $M = 10^6 M_\odot$

$t \sim 80$ Myr $(r/100$ pc$)^2$

varies in $1/M$

Gas is piling up in the center: up to $f=90\%$

Hopkins et al 2011
A second gas rings + outflow

NGC 1433: barred spiral, CO(3-2) with ALMA
Molecular gas fueling the AGN, + outflow // the minor axis

\[ M_{H_2} = 5.2 \times 10^7 \, M_{\odot} \text{ in FOV}=18'' \]
100km/s flow
7% of the mass = 3.6 \times 10^6 \, M_{\odot}
Smallest flow detected

\[ L_{\text{kin}} = 0.5 \, \text{dM/dt} \, v^2 \approx 2.3 \times 10^{40} \, \text{erg/s} \]
\[ L_{\text{bol}} \, (\text{AGN}) = 1.3 \times 10^{43} \, \text{erg/s} \]
Combes et al 2013

Gravity torques fuel the ring, where gas is stalled
Smajic et al 2014
Torques are positive inside 200pc and negative outside

⇒ Gas is piling at the 2nd ring

2nd ring at 200pc = ILR of the nuclear bar
The NGC1566 barred Sy1: feeding phase

N1566  SAB  Sy1

Spatial resolution
0.5 arcsecond ~25pc

Combes et al 2014

Overlay CO(3-2) contours on HST image
Periodic orbits in a potential in \( \cos 2\theta \)

The gas tends to follow these orbits, but rotates gradually by 90° at each resonance

a) without BH, leading

b) with BH, trailing

Stellar periodic orbits
NGC1566: gravitational torques

Gas is driven inwards

Trailing spiral inside the ILR ring of the bar

⇒ BH influence on the dynamics
NGC 1808

Trailing nuclear spiral ➔ Fueling the BH

Audibert et al. 2019
NGC 1808
Salak et al 2017

CO32 contours on HST

CO32 beam 1"

CO32 contours on continuum

12' & 25'

CO (3-2) velocity field

CO (3-2)/CO (1-0) intensity ratio

bar (ridge)

500 pc pseudoring

CMCs

CND

nuclear spiral
Trailing nuclear spiral  ➔  Fueling the BH

NGC 1808

Audibert et al 2019
NGC 1808

No outflow in CO close to the center

But outflow at larger scale → Due to starburst

CO(3-2)
With 0.09” x 0.06” resolution (5pc): nuclear spiral + torus

Combes et al 2019
NGC 613: Outflow

Average gravity torque

The gas infalls in 1 rotation~10Myr

\[ M_{\text{out}} = 2 \times 10^6 \, M_\odot \]

\[ \dot{M}_{\text{out}} = 15 \, M_\odot /\text{yr} \]

Audibert et al 2019
Flow parallel to the radio jet

The molecular torus is $R = 14\text{pc} = 0.17''$

Difficult to disentangle with the outflow, of size $R_{\text{out}} = 23\text{pc} = 0.28''$, $V_{\text{out}} = 300\text{km/s}$

But reverse sense!
Two main modes for AGN feedback

Quasar mode: radiative or winds
When \( L \) close to Eddington, young QSO, high \( z \)
\( L_{\text{Edd}} \sim M_{\text{BH}} / \sigma_T \rightarrow M_{\text{BH}} \sim f \sigma_T \sigma^4, \ f \) gas fraction

Same consideration with radiation pressure on dust, with \( \sigma_d \)
\( \sigma_d / \sigma_T \sim 1000, \) limitation of \( M_{\text{bulge}} \) to 1000 \( M_{\text{BH}} \) ? (e.g. Fabian 2012)

Radio mode, or kinetic mode, jets
When \( L < 0.01 L_{\text{edd}} \), low \( z \), Massive galaxies, Radio E-gal
*Radiatively inefficient flow ADAF*

High frequency of cooling flows in clusters,
Low-luminosity AGN, Seyferts
Offcentered nucleus and outflow in NGC1068

Black $V=-50$ km/s
White $V=50$ km/s

Outflow of $63M_\odot$/yr
10x the star formation rate in this region

Garcia-Burillo, Combes, Usero et al 2014
Detection of molecular tori

ALMA CO(6-5) and 432µm dust emission

Torus of 7-10pc in diameter in NGC1068

More inclined than the H₂O maser disk

Papaloizou-Pringle instability

Garcia-Burillo, Combes, Ramos-Almeida et al 2016, R=3.5pc torus
Molecular torus inside a polar dusty cone

1'' = 50 pc, Gratadour et al 2015 SPHERE NIR

X-rays, XMM, Nustar
Several components
From $10^{23}$ cm$^{-2}$
up to $10^{25}$ cm$^{-2}$
\(\Rightarrow\) Compton-thick
\(~\) up to 100 pc scale
Bauer et al 2015
Marinucci et al 2016
Polar dust distribution

Green: 100pc along the polar axis

Asmus et al 2016

149 AGN, 21 show extended dust distribution, 18 on the polar axis (MIR) Aligned with [OIII], [OIV] radio, masers, etc..

Dusty winds, associated to the molecular outflows?
NGC1326

Liner, (R1)SB(rl)0/a

10''
720pc

1'' (72pc)
Frequency of « molecular tori »: 7/8

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Radius (pc)</th>
<th>M(H$_2$)$<em>a$ $10^7$ $M</em>\odot$</th>
<th>inc(°) torus</th>
<th>inc(°)$_b$ gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 613</td>
<td>14±3</td>
<td>3.9±1.4</td>
<td>46±7</td>
<td>36</td>
</tr>
<tr>
<td>NGC 1326</td>
<td>21±5</td>
<td>0.95±0.1</td>
<td>60±5</td>
<td>53</td>
</tr>
<tr>
<td>NGC 1365</td>
<td>26±3</td>
<td>0.74±0.2</td>
<td>27±10</td>
<td>63</td>
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<tr>
<td>NGC 1433</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>67</td>
</tr>
<tr>
<td>NGC 1566</td>
<td>24±5</td>
<td>0.88±0.1</td>
<td>12±12</td>
<td>48</td>
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<tr>
<td>NGC 1672</td>
<td>27±7</td>
<td>2.5±0.3</td>
<td>66±5</td>
<td>28</td>
</tr>
<tr>
<td>NGC 1808</td>
<td>6±2</td>
<td>0.94±0.1</td>
<td>64±7</td>
<td>84</td>
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<tr>
<td>NGC 1068</td>
<td>3.5</td>
<td>0.01</td>
<td>80</td>
<td>24</td>
</tr>
</tbody>
</table>
NGC 1672 \textit{(Jenkins et al 2011)}

Sy 2, SB(s)b\quad SF in the ring at ILR $R=300\text{pc}$
NGC 1672

- Sy 2, SB(s)b
- 11.4 Mpc, i~30°
- 3pc resolution

15'' (820pc) CO32

Torus edge-on  R=16pc

Beam 0.09'' x 0.06''

Combes et al 2019
NGC 1672

CO32-contours on continuum

HCN(4-3) & HCO+(4-3) just detected in the center

1 arcsec = 55pc
NGC 1672

Diaz et al 1999: Hα velocity field, at kpc scale
N1672: Black hole mass

With BH, of \( M = 5 \times 10^7 \) M\(_\odot\)
Potential from NIR galfit, Sersic components

- The bulge in red, the disk in green, the bar in blue, nucleus in cyan

Simulations of gas in the potential, with possibility of varying incl, PA
Rotational $V$ with $Q_{\text{toom}}=1$. Building a data cube, and projecting
Normalised to the 2D moment-0 CO map, at each pixel.
Model

Observations

Intensity $V$

$\sigma$

$2.5 \times 10^7 \, M_\odot$

$5 \times 10^7 \, M_\odot$
Modelisation of NGC 1365

Model

Observed
WISDOM project: NGC 3665 Onishi et al 17

CO(2-1), Beam 0.60x0.56” = 100x93pc 1” = 167pc
WISDOM project: NGC 4697  *Davis et al 17*

CO(2-1), Beam 0.54x0.52'' = 30x 29pc

**No BH**  
**1.2 \(10^8\) M\(_\odot\)**  
**Best Fit**
WISDOM project: NGC 4429  

Davis et al 17

CO(3-2), Beam 0.18x0.14'' = 14x11 pc  D=16.5 Mpc  1'' = 80 pc

**Best Fit**

No BH

1.5 $\times 10^8 M_\odot$

Best Fit
Compilation van den Bosch 2016
Slope 5.35

\[ \log \text{MBH (M}_\odot) \]

\[ \log \sigma \text{ (km/s)} \]

▲ from CO line
Non-alignment with host disk

Like in the MW, the nuclear disks are not aligned with the galaxy, nor the ISM nuclear disks.

In NGC 4258, the maser disk 0.2pc in size is misaligned by 119° from the galaxy disk, the jet is in the plane.

Many Seyfert have their jet not perpendicular to the main disk (Schmitt & Kinney 2002; Jog & Combes 2009)

CNR: circumnuclear ring
2-3pc in radius
HCN in orange
Ionized gas in green
Inclination of 20°/plane

Mini-spiral 60M☉
Cavity 200M☉
CNR 10°M☉
7 x 10⁴ cm⁻³
300K
CMZ in the Milky Way

3 \(10^7\) Mo cold gas, 60x100pc, x2 orbit, SgrA* off-centered \(\Rightarrow m=1\)

Why no SFR in the 500pc-center?

Kruijssen et al 2014

Herschel

Molinari et al 2011
Non-alignment of rings

CNR: circumnuclear ring
R=2-3pc
orange = HCN
Green= Ionized gas
Inclination of 20°/plane

Rodriguez-Fernandez & Combes 2008
High-resolution simulation of the Milky Way
Zoom in the central 200pc region

Face-on

Renaud et al, Emsellem et al 2014
How the gas is accreted

Strong SN Feedback

→ Gas in the perpendicular plane

Emsellem et al 15

Inclined
Circumnuclear ring

Face-on

Edge-on

Polar disk face-on
SUMMARY

- **Fueling:** Primary bar drives gas $\rightarrow$ 100pc
  Then nuclear bar from 100pc to 10pc

- **At scales $\sim$1-10pc,** macro-turbulence, clumps, warps, dynamical friction, formation of **thick disks/torus**

- **Feedback:** outflows due to starbursts and to AGN
  Strong coupling due to mis-alignment

- **Mis-alignment between small scales and large scales**
  due to accretion, and different dynamical time-scales,