Molecular gas dynamics around nuclei of galaxies

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Abstract. Recent molecular line observations with ALMA in several nearby Seyferts have revealed the existence of molecular tori, and the nature of gas flows at 10-20 pc scale. At 100 pc scale, or kpc-scale, previous NOEMA work on gravitational torques had shown that only about one third of Seyfert galaxies experienced molecular inflow and central fueling, while in most cases the gas was stalled in rings. At higher resolution, i.e. 10-20 pc scale, it is possible now to see in some cases AGN fueling due to nuclear trailing spirals, influenced by the black hole potential. This brings smoking gun evidence for nuclear fueling. In our sample galaxies, the angular resolution of up to 60 mas allows us to reach the black hole (BH) sphere of influence and the BH mass can be derived more directly than with the M-sigma relation.

1 Introduction

Our vision of the close environment of the black hole and its accretion disk has evolved significantly in the recent years. While the geometrical orientation paradigm helped to understand the difference between type 1 and 2 AGN, through the presence of a dusty torus at parsec scale (e.g. Urry & Padovani 1995), it is possible that the required obscuration is only due to outflowing dust in a hollow polar cone (Asmus et al. 2016). Around the accretion disk, and the ionised Broad Line Region (BLR), dust cannot survive due to high temperatures, but at the sublimation radius, radiation pressure pushes the dust in the polar cone. Gas and dust are inflowing through a molecular disk, where sometimes water masers are seen, and also H_2 and CO emission lines. The disk is likely to be flaring, i.e. its thickness is increasing strongly with radius (Hönig, 2019).

In the following, I will describe:

1- how the AGN feeding occurs, how the gas angular momentum is transferred through gravity torques from dynamical features, nuclear bars and spirals, and how the gas accumulates in a molecular torus

2- how the AGN feedback develops, aided by supernovae feedback. The two main modes, radiative or kinetic mode, through winds and radio jets, may occur simultaneously, and result in significant molecular outflows at intermediate scales.

2 Fueling

One of the first galaxy mapped with ALMA at high angular resolution is NGC 1566 (Combes et al. 2014). This is a barred spiral galaxy, with an inner Lindblad resonance ring inside the

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bar. The field of view (FOV) of ALMA at the CO(3-2) line at 345.796 GHz is 18”, ending just at the border of the ring, which has then a low signal-to-noise ratio.. Inside the resonant ring, there exists a nuclear disk, revealed by ALMA. This disk shows a nuclear spiral, which is trailing, i.e. the same winding sense as the spiral structure outside of the bar, as seen in figure 1.

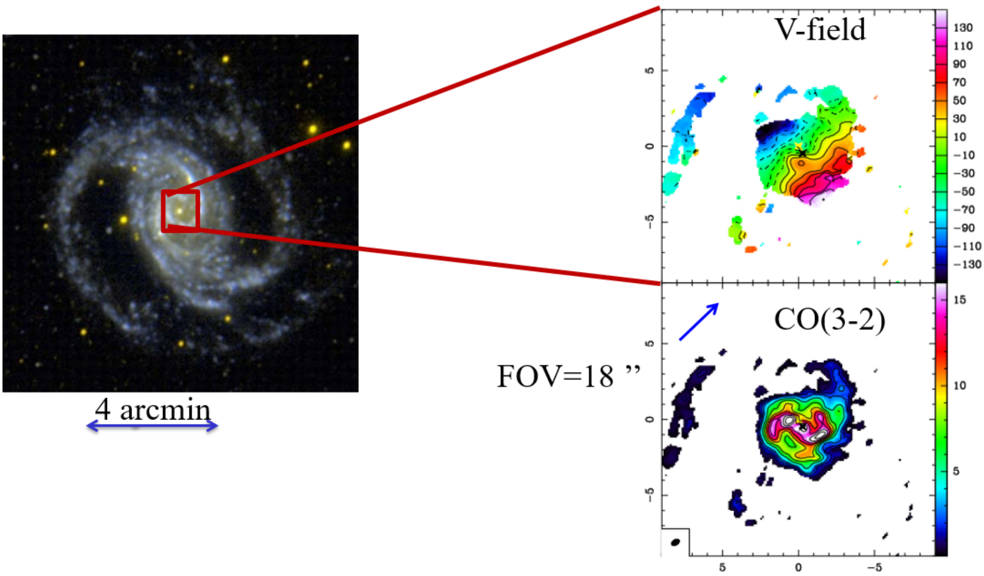

Figure 1. NGC 1566 observed in CO(3-2) with ALMA. The left image shows the large-scale barred spiral structure, and the inner Lindblad resonance (ILR) ring inside the bar, corresponding to the FOV of 18”. The two first moments at right reveals a trailing nuclear spiral, inside a nuclear disk, with relatively regular velocity field (adapted from Combes et al. 2014).

2.1 Gravity torques

The main issue in the fueling process is to get rid of the high angular momentum of the gas. While viscous torques are inefficient in galactic disks down to sub-pc scales, gravity torques from tidal forces in the outer parts, and bars in the inner parts, are able to exchange angular momentum in between resonances (e.g. Buta & Combes 1996). Bars are ending just before their corotation (CR) radius, where the bar pattern speed equals the angular speed of the tars and gas. Then the torques exerted on spiral arms just outside the bar are positive, and drive the gas to the OLR (Outer Lindblad Resonance). Inside the CR radius, torques are negative down to the ILR, but then change sign inside ILR (Inner Lindblad resonance), and may give rise to a leading spiral. This ensures that gas is accumulating at the ILR ring.

However, the precessing rate $\Omega-\kappa/2$ of the elliptical orbits, which is usually an increasing function of radius inside ILR, may change behaviour close to the nucleus, due to the gravitational influence of the black hole (BH). The rotational velocity Ω, the epîcyclic frequency κ, and the precessing rate $\Omega-\kappa/2$ are then dominated by the keplerian potential, and decrease with radius in the central 10-20 pc. This reverses the winding sense of the gas spiral, and trailing nuclear spirals are expected in the sphere of influence (SoI) of the BH cf Figure 2.

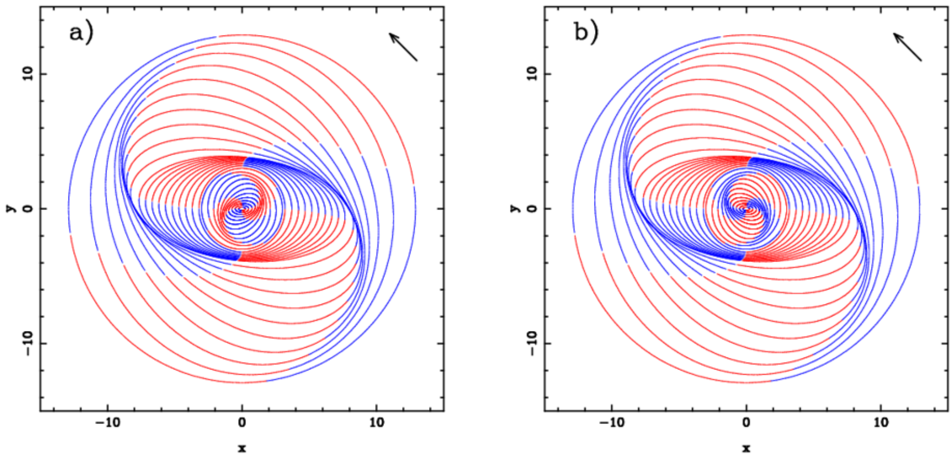

Figure 2. Left: Schematic representation of the gas streamlines in a barred galaxy, where ILRs exist. The bar is horizontal. When there is no central mass concentration, and the precessing rate $\Omega - \kappa/2$ decreases towards the center, the gas is crowding in a leading nuclear spiral, and the torque exerted is positive. **Right:** When there is a supermassive black hole dominating inside the ILR, the precessing rate $\Omega - \kappa/2$ increases again towards the center, and the dissipating gas follows now a trailing spiral. The torque is negative, and the gas may fuel the nucleus. The arrow indicates the sense of rotation. The colors indicate the sign of the torques, blue: negative and red: positive.

This also reverses the sign of torques, which are now negative, and drive the gas to the center, fueling the BH.

2.2 Trailing nuclear spirals, molecular tori

The trailing nuclear spiral detected in NGC 1566 explains the feeding of the AGN. These nuclear spirals are frequently observed, when the angular resolution is sufficient. It is also detected in NGC 613 with 0.09”×0.06” resolution (5 pc, Combes et al. 2019, Audibert et al. 2019) but not with 0.5” resolution (Miyamoto et al. 2017). It is detected in NGC 1808 (Audibert et al. 2021), and in dense gas tracers HCO+, HCN and CS, as seen in figure 3.

Inside these nuclear spirals, a molecular disk is detected, with apparent decoupled morphology and kinematics. We call these nuclear disks molecular tori, they are detected in most of our observed sample of Seyferts (Combes et al. 2019). They might be related to the dusty tori of the classical AGN unification scheme. Their orientation appears randomly distributed with respect to that of the large-scale galaxy disk. The sizes of molecular tori are typically 10-20 pc, and are contained in the SoI. Their molecular mass is of the order of a few 10^7 $M_\odot$.

When the resolution is enough inside the BH sphere of influence, it is possible to determine the BH mass, with a proper modelisation of the tilted molecular torus (e.g. Poitevineau et al. 2022). Figure 4 shows examples of galaxies from the GATOS survey (Garcia-Burillo et al. 2021), where this is possible, albeit the tilted orientation of the nuclear disk.

3 Feedback

Molecular outflows are frequently observed in nearby Seyferts, and can be quite small (<1kpc), with low velocity ~ 100 km/s (NGC 1433, Combes et al. 2013). They are often

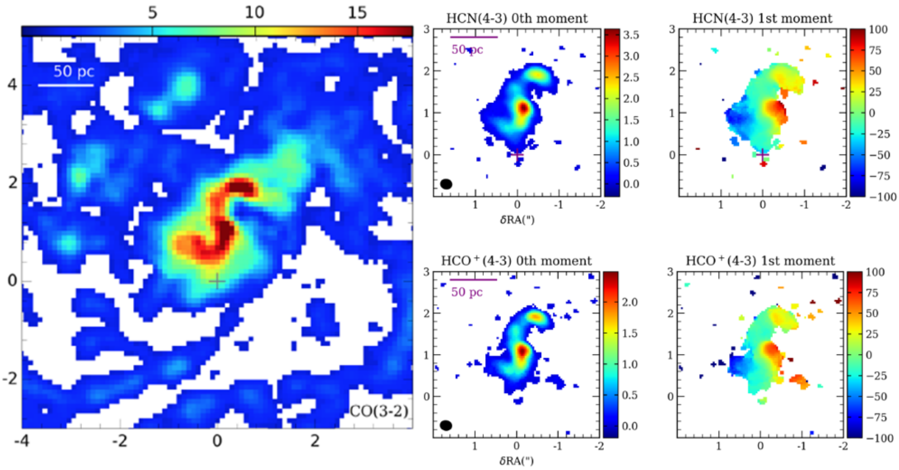

Figure 3. Nuclear spiral detected in NGC 1808 in CO(3-2) (left) and HCN(4-3), HCO+(4-3) (right), with a beam of 0.08" = 4 pc. The velocity field inside the nuclear spiral has a different major axis orientation from the large-scale one (adapted from Audibert et al. 2021).

associated to small radio jets (NGC 613, Audibert el al. 2019), although sometimes very collimated molecular outflows can occur without a detectable radio jet (NGC 1377, Aalto et al. 2016, 2019).

Several mechanisms have been invoked to produce these molecular outflows, some are purely due to star formation feedback, but then their power is not related to the AGN luminosity (Cicone et al. 2014). If the AGN is more luminous than 0.01 Eddington luminosity, radiation pressure on the ionised gas triggers a fast outflow in the nucleus, which then entrains the molecular gas. In the case of low-luminosity AGN (lower than 0.01 Eddington), only radio jets can entrain the molecular gas (kinetic mode). At the transition luminosities, both can be present, in particular radio jets and winds driven by radiation pressure on dust (Sadowski et al. 2013).

With high angular resolution, it is possible to disentangle AGN from supernovae feedback: for instance, the galactic wind in NGC 1808, must be a starburst driven wind, since there is no molecular outflow towards the nucleus (Audibert et al. 2021).

Radio jets appear quite coupled to galaxy disk, to produce molecular outflows, since they are not in general perpendicular to the disk. Frequently they can sweep out gas from the inner disk, as in NGC 1068 where the outflow rate reaches 63 $M_\odot$/yr (Garcia-Burillo et al. 2014, 2016). This prototypical Seyfert-2 reveals an edge-on molecular torus, perpendicular to the radio jet, and a molecular outflow, plus a hollow polar cone seen beautifully in polarised near-infrared light (Gratadour et al. 2015). The column density in the molecular torus and extended dust cone is sufficient to account for the BLR obscuration.

The most collimated molecular outflow has been found in the early-type galaxy NGC 1377 (Aalto et al. 2016, 2019). The molecular jet is almost in the plane of the sky, precessing by about 10°, and therefore it alternates in radius blue and red-shifts. While a radio source is detected in the center at cm wavelengths, there is no radio jet within the detection limit, which might yield insight in the jet life-time. The relativistic jet could disappear in less than 3000 yr, while the molecular jet will remain for more than 3 Myr.

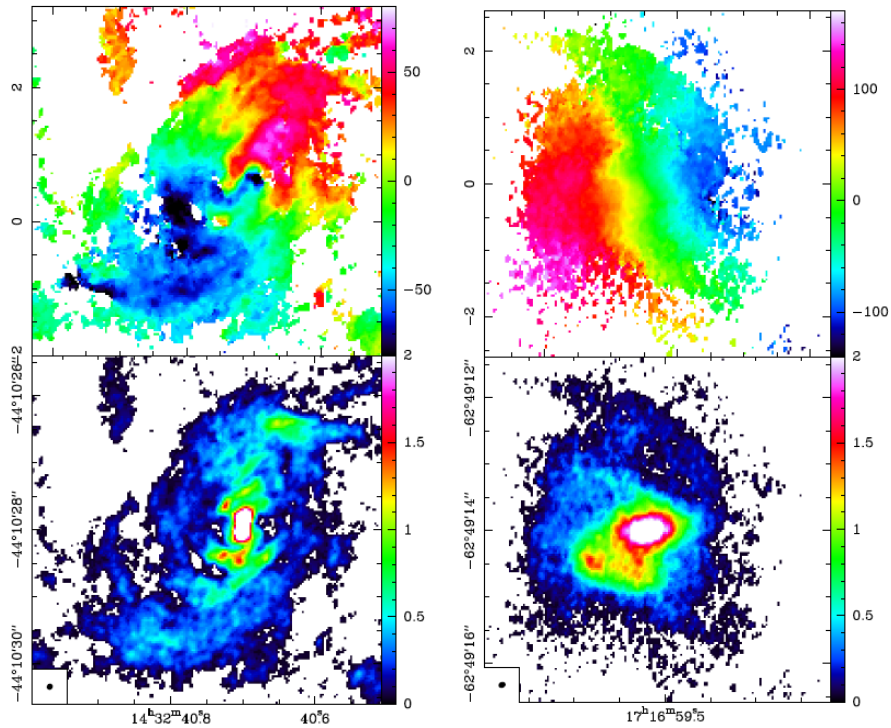

Figure 4. Two galaxies, NGC 5643 (left) and NGC 6300 (right) observed in CO(3-2) with ALMA, from the GATOS sample (Garcia-Burillo et al. 2021). The two first moments show the more or less tilted kinematical major axis in the nucleus (adapted from Poitevineau et al. 2022).

4 Summary

High angular resolution has brought a lot of informations about the AGN fueling. Non-axisymmetric features (bars, spirals, interactions) produce gravity torques, allowing exchange of angular momentum. The gas may be quicky driven towards the center, through a trailing nuclear spiral, and accumulate in a molecular torus, with decoupled morphology and kinematics.

High resolution can also help disentangle the origin of the feedback, AGN or supernovae. Molecular outflows are frequent and may be driven by radio jets or winds (or both). In case of AGN feedback, the molecular outflows are misaligned with the rest of the large-scale disk. The outflows are more likely energy-driven with AGN, while momentum-driven with starbursts. In the latter case, the feedback is weaker, with the ejected gas rapidly infalling back after a fountain episode, only postponing star formation without quenching it.

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