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# New views on bar pattern speeds from the NUGA survey

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**Abstract.** We present a review on bar pattern speeds from preliminary results in the context of the Nuclei of Galaxies (NUGA) project. The large variety of molecular circumnuclear morphologies found in NUGA is a challenging result that implies the refinement of current dynamical models of galaxies.

**Key words.** galaxies: active – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: spiral

## 1. Introduction

Accretion of gas onto supermassive black holes (SMBHs) in galactic centers is the source of active galactic nuclei (AGN) activity. AGN must be fed with material coming from the disk of the host galaxy, far away from the influence of the SMBH, and this implies that the gas supply should lose its angular momentum during the fueling process. Different mechanisms for removing the gas angular momentum have been proposed, processes which can be accomplished through non-asymmetric perturbations. Gravitational torques due to density waves (e.g., spirals, bars, and lopsidedness perturbations) or galaxy-galaxy interactions (e.g., galaxy collisions, mergers, close encounters, and mass accretion) are capable of removing angular momentum of the rotating gas. The study of molecular gas, the predominant phase of the interstellar medium in the nuclei of spiral galaxies, is fundamental to investigate in detail how AGN activity is related to the molecular gas morphology and kinematics. The connection between AGN and molecular gas is

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**Table 1.** NUGA galaxies studied in detail.

| Galaxy | SB/GB/OD† (kpc) | SR/GR† (kpc) | $\Omega_p$ (km $s^{-1}$ $kpc^{-1}$) | Predicted resonances† |
|---|---|---|---|---|
| | | Galaxies with inflow | | |
| NGC 6574 | $r_{NSB}$ = 0.6 | | | |
| | $r_{PSG}$ = 1.6 | $r_{OGR}$ = 1.6 | 65 | $r_{UHR}$ = 1.6 |
| | | $r_{IGR}$ = 0.13 | | $r_{IILR}$ = 0.03 − 0.9 |
| | | | | $r_{OILR}$ = 1.0 |
| | | | | $r_{CR}$ = 2.8 |
| NGC 2782 | $r^{DB}_{NSGB}$ = 1.0 | $r_{IGR}$ = 0.3 | 270 | $r_{ILR}$ = 0.2 − 0.5 |
| | | | | $r_{CR}$ = 1.1 |
| | $r^{DB}_{PSB}$ = 2.5 | $r_{OGR}$ = 1.0 | 65 | $r_{ILR}$ = 1.3 |
| | | | | $r_{UHR}$ = 3.6 − 3.8 |
| | | | | $r_{CR}$ = 5.0 |
| NGC 3147 | $r_{PSB/OD}$ = 1 − 1.5 | $r_{IGR}$ = 2.0 | 125 | $r_{UHR}$ = 2.0 |
| | | | | $r_{CR}$ = 3.0 |
| | | $r_{OGR}$ = 4.0 | | |
| NGC 4579 | $r^{DB}_{NSB/OD}$ = 0.2 | $r_{ISB}$ = 0.2 | 270 | $r_{UHR}$ = 0.2 |
| | | | | $r_{CR}$ = 1.0 |
| | $r^{DB}_{PSB}$ = 6.0 | | 50 | $r_{IILR}$ = 0.5 |
| | | $r_{OGR}$ = 1.0 | | $r_{OILR}$ = 1.3 |
| | | | | $r_{UHR}$ = 3.8 |
| | | | | $r_{CR}$ = 6.0 |
| | | Galaxies without inflow | | |
| NGC 4826 | $m$ = 1 fast trailing spiral waves | | 1500 | $r_{CR}$ = 0.1 |
| | | | | $r_{OLR}$ = 0.35 |
| NGC 7217 | $r_{OD}$ = 3.7 | $r_{NSGR}$ = 0.8 | 80 | $r_{ILR}$ = 1.0 |
| | | $r_{ISR}$ = 2.2 | | $r_{UHR}$ = 2.2 |
| | | | | $r_{CR}$ = 3.7 |
| | | $r_{OSR}$ = 5.4 | | $r_{OLR}$ = 4.0 − 5.0 |
| NGC 4569 | $r_{PSGB}$ = 3.3 | | 60 | $r_{ILR}$ = 0.6 |

NOTES. † These quantities are uncertain to roughly ±20%. ILR = inner Lindblad resonance, IILR = inner ILR, OILR = outer ILR, OLR = outer Lindblad resonance, UHR = ultra-harmonic resonance, CR = corotation, DB = decoupled bars, SB = stellar bar, GB = gas bar, NSB = nuclear stellar bar, NSGB = nuclear stellar/gas bar, ISB = inner stellar bar, PSB = primary stellar bar, PSGB = primary stellar/gas bar, SR = stellar ring, NSGR = nuclear stellar gas ring, ISR = inner stellar ring, OSR = outer stellar ring, GR = gas ring, IGR = inner gas ring, OGR = outer gas ring, OD = Oval distortion.

also complicated by the presence of different scales, both spatial and temporal. The AGN duty cycle ($\sim 10^{5-6}$ yr) should be shorter than the lifetime of the feeding mechanism (e.g., Wada 2004), and at present the critical spatial scales for AGN feeding (<10-100 pc) can only be achieved with mm-interferometers in nearby low-luminosity AGN (LLAGN).

The NUclei of GAlaxies (NUGA) project, a large-scale international collaboration for a high-resolution ($\leq$ 1″) and high-sensitivity carbon monoxide (CO) survey made with the Plateau de Bure IRAM interferometer, has been initiated to better understand the mechanisms for gas fueling of AGN. The survey is based on a sample of 12 nearby LLAGN, which span the whole sequence of activity types (Seyferts, LINERs, and transition objects). NUGA galaxies already analyzed show a 'zoo' of molecular gas morphologies which characterize the inner kpc of the galaxies. These morphologies include one and two armed instabilities (García-Burillo et al. 2003; Krips et al. 2005), rings and nuclear spirals (Combes et al. 2004; Casasola et al. 2008), and large-scale bars and two-arm spirals (Boone et al. 2007; Lindt-Krieg et al. 2008; Hunt et al. 2008; García-Burillo et al. 2009).

Here, we present the first results regarding bar pattern speeds obtained with a statistical review of NUGA galaxies already analyzed in detail.

## 2. NUGA analysis

### 2.1. CO morphologies

For each NUGA galaxy, we study the overall distribution of the molecular gas in the inner kpc, both in $^{12}$CO(1-0) and $^{12}$CO(2-1) emission. Fig. 1 shows the CO morphology found for the starburst/Seyfert 1 NGC 2782 (Hunt et al. 2008). The $^{12}$CO(1-0) emission is aligned with the nuclear stellar bar of radius $\sim$1 kpc. At the ends of the nuclear bar, the CO changes direction and traces diffuse asymmetric spiral arms extending to the north and south and aligned with an outer stellar oval reminiscent of a weak primary bar.

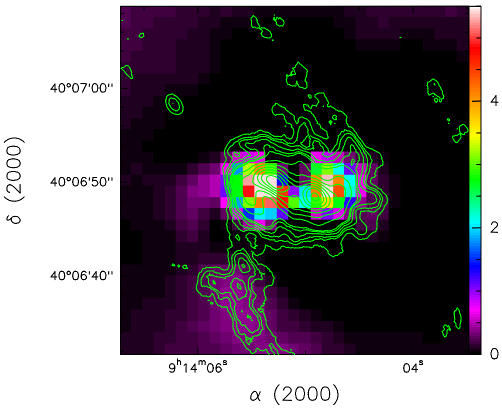

**Fig. 1.** $^{12}$CO(1-0) total intensity contours (green) overlaid on the *residuals* (in MJy sr$^{-1}$) of the bulge-disk decomposition performed on the 3.6 $\mu$m Spitzer/IRAC for NGC 2782 (Hunt et al. 2008).

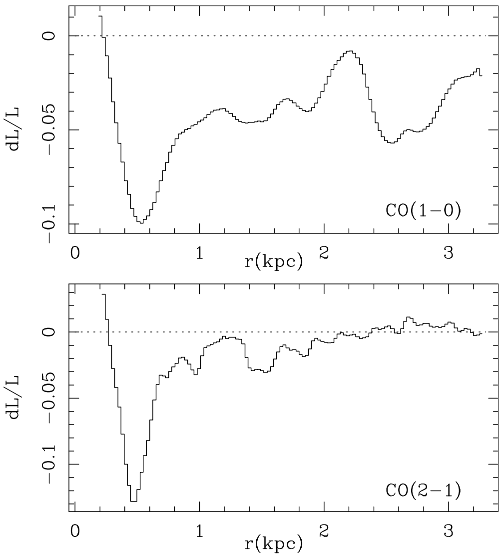

**Fig. 2.** The relative torque, $dL/L$, derived for NGC 2782 in $^{12}$CO(1-0) (upper panel) and $^{12}$CO(2-1) (lower panel) using the potential obtained from the 3.6 $\mu$m Spitzer/IRAC image.

### 2.2. Gravity torques

The NUGA analysis continues by interpreting the distribution and kinematics of the gas, case-by case, in terms of feeding mechanisms. To do this, we compute the gravitational torques by first using high-resolution optical and near-infrared images of the galaxies to derive gravitational potential. We can then quantify the efficiency of the stellar potential to drain the gas angular momentum: negative torques mean that the gas is losing angular momentum and flowing into the central regions, while positive torques are driving the gas outwards. Fig. 2 shows the relative torques, $dL/L$, derived for

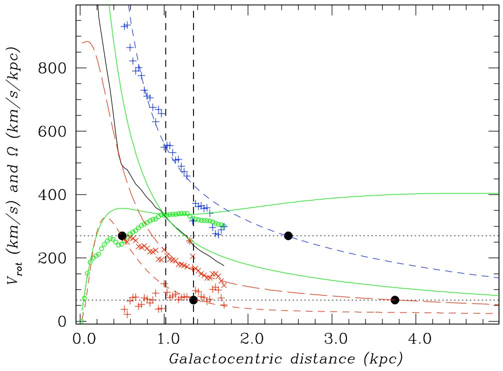


**Fig. 3.** Rotation and derived frequency curves $\Omega$, $\Omega \pm k/2$ and $\Omega - k/4$, and the empirical ones derived from our $^{12}$CO observations for NGC 2782. The vertical dashed lines indicate the nuclear bar length (~1 kpc) and the ILR of the outer oval (~1.3 kpc), close to CR of the nuclear bar (~1.1 kpc). For details see Hunt et al. (2008).

NGC 2782 from the 3.6 $\mu$m Spitzer/IRAC image. Both $^{12}$CO(1-0) and $^{12}$CO(2-1) emission give a similar picture: *the average torques are negative in the inner few kpc of NGC 2782, down to the resolution limit of our images.*

### 2.3. Rotation curves

The final step is to derive the rotation curve from our CO observations and to compare it with derived frequency curves. Fig. 3 shows this comparison performed for NGC 2782. In this figure, one can identify the nuclear bar with $\Omega_b \sim 270\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ and corotation (CR) at ~1.1 kpc, and the primary bar with $\Omega_b \sim 65\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ and an inner Lindblad resonance (ILR) at ~1.3 kpc, very close to the CR of the nuclear bar.

## 3. Bar pattern speeds and resonances

By analyzing the gravitational torques on the molecular gas, we found net inflow in four galaxies studied in detail so far, with particularly strong cases in NGC 2782 and NGC 4579. Table 1 summarizes the first results obtained considering seven NUGA galaxies. *The common feature shared by NGC 2782 and NGC 4579 is two decoupled bars with overlapping resonances: one bar is rapidly rotating ($\Omega_b \sim 270\,km\,s^{-1}\,kpc^{-1}$) and the other rotates more slowly ($\Omega_b \sim 50 - 65\,km\,s^{-1}\,kpc^{-1}$).* Such resonances and kinematic decoupling are fostered by a large central mass concentration (e.g., stellar bulge) and high gas fraction.

## 4. Conclusions

The analysis of the whole NUGA sample will provide a clearer picture on the distribution and kinematics of molecular gas in the nuclei of AGN and on the different mechanisms for gas fueling. NUGA also represents a pilot study for the investigation of fueling mechanisms at high redshift, which will be possible thanks to instruments of the immediate future, such as ALMA.

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## References

Boone, F., Baker, A. J., Schinnerer, E., et al. 2007, A&A, 471, 113
Casasola, V., Combes, F., García-Burillo, S., et al. 2008, A&A, 490, 61
Combes, F., García-Burillo, S., Boone, F., et al. 2004, A&A, 414, 857
García-Burillo, S., Combes, F., Hunt, L. K., et al. 2003, A&A, 407, 485
García-Burillo, S., Fernandez-Garcia, S., Combes, F, et al. 2009, A&A, 496, 85
Hunt, L. K., Combes, F., García-Burillo, S., et al. 2008, A&A, 482, 133
Lindt-Krieg, E., Eckart, A., Neri, R., et al. 2008, A&A, 479, 377
Krips, M., Eckart, A., Neri, R., et al. 2005, A&A, 442, 479
Wada, K. 2004, in Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge Univ. Press, Cambridge), 186