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# Probing the Gas Fueling and Outflows in Nearby AGN with ALMA

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Feeding and feedback in AGN play a very important role to gain a proper understanding of galaxy formation and evolution. The interaction between activity mechanisms in the nucleus and its influence in the host galaxy are related to the physical processes involved in feedback and the gas fueling of the black hole. The discovery of many massive molecular outflows in the last few years have been promoting the idea that winds may be major actors in sweeping the gas out of galaxies. Also, the widely observed winds from the central regions of AGN are promising candidates to explain the scaling relations (e.g., the black hole-bulge mass relation, BH accretion rate tracking the star formation history) under the AGN feedback scenario. Out goal is to probe these phenomena through the kinematic and morphology of the gas inside the central kpc in nearby AGN. This has recently been possible due to the unprecedented ALMA spatial resolution and sensitivity. We present results on NGC7213 and NGC1808, the latter is part of a new ALMA follow-up of the NuGa project, a previous high-resolution (0.5–1″) CO survey of low luminosity AGN performed with the IRAM PdBI.

**Keywords: active galactic nuclei, extragalactic astronomy, evolution of galaxies, galaxies, spectroscopy**

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## 1. INTRODUCTION

The fueling of SMBH at the center of galaxies and the subsequent feedback from its active nuclei, are among the key processes to understand the concerted growth of galaxies and BH. AGN feedback is invoked to explain the formation of massive galaxies when we compare the luminosity function of galaxies to theoretical simulations based on the cold dark matter models (Silk and Mamon, 2012). Winds and outflows produced by the AGN can eject or heat the gas, terminate the star formation and through the lack of fuel for accretion, quench the black hole activity. Recent discovery of many massive molecular outflows (e.g., Feruglio et al., 2010; Fischer et al., 2010; Alatalo et al., 2011; Sturm et al., 2011; Dasyra and Combes, 2012; Veilleux et al., 2013; Cicone et al., 2014; Dasyra et al., 2014; García-Burillo et al., 2014) have been promoting the idea that winds may be major actors in sweeping the gas out of galaxies, in agreement with theoretical predictions of AGN driven winds models (Faucher-Giguère and Quataert, 2012; Zubovas and King, 2012, 2014). However, it is still difficult to distinguish the origin of the outflows, whether they are AGN-driven or starburst-driven.

On the other hand, AGN are fueled by accretion of material onto the BH and the gas component can form stars on its way to the BH (García-Burillo and Combes, 2012; Combes et al., 2014). It is important to study the efficiency of angular momentum transport in galaxy disks in order to understand how the star formation and nuclear activity are fueled and what are the timescales involved, since both feeding process rely on a common cold gas supply, but in very different periods of time ($\sim 10^5$ year for BH growth and $\sim 10^{7-9}$ year for star formation; García-Burillo, 2016). In addition to this scenario, one of the outstanding problems is to identify the mechanism that drives gas from the disk toward the nucleus, removing its large angular momentum and forming large non-axisymmetric perturbations, such as bars or spirals.

This work aims to better understand the galaxies chemical and thermal evolution by studying in detail the physical processes acting on the nucleus of a sample of nearby AGN. Probing AGN feeding and feedback phenomena through the kinematic and morphology of the gas inside the central kpc have recently been possible due to the unprecedented Atacama Millimeter/Submillimeter Array (ALMA) spatial resolution ($\lesssim 0.5''$) and sensitivity. Since there are only a few AGN observed with high spatial resolution, we investigate the nuclear molecular emission in a sample of nearby AGN making use of spectroscopic techniques.

## 2. METHODOLOGY

By applying the velocity channel maps on the dense molecular gas tracers, e.g., HCN, $HCO^+$, CS, and mid transition of CO, we can access the gas kinematics. To detect possible inflows or outflows, we can compare the CO rotation curve with a rotational velocity model based on the H$\alpha$ kinematics and then subtract the model to analyse the velocity residuals in order to search for blue and redshifted patterns. Another possibility is to explore the current models for the rotation curve, when previous H$\alpha$ or H I are not available in the literature. One of this model is described by Bertola et al. (1991), assuming the gas is on circular orbits in a plane, $\upsilon_c = Ar/(r^2 + c^2)^{p/2}$, where for $p = 1$ the velocity curve is asymptotically flat and $p = 3/2$ the system has a finite total mass, therefore we expect $1 \leq p \leq 3/2$. The observed radial velocity at a position (R, $\Psi$) on the plane of the sky can be described as:

$$\upsilon_{mod}(R,\Psi) = \upsilon_{sys} + \frac{ARcos(\Psi - \Psi_0)sin(\theta)cos^p(\theta)}{\left\{R^2\left[sin^2(\Psi - \Psi_0) + cos^2(\theta)cos^2(\Psi - \Psi_0)\right] + c^2cos^2(\theta)\right\}^{p/2}} \quad (1)$$

where $\theta$ is the inclination of the disk (with $\theta = 0$ for a face-on disk), $\Psi_0$ is the position angle of the line of nodes, $v_{sys}$ is the systemic velocity and $R$ is the radius and $A$, $c$, and $p$ are parameters of the model. In the cases of NGC 7213 and NGC 1808, we have used the Bertola et al. (1991) model to search for non-circular motions in their observed velocity field.

## 3. RESULTS

### 3.1. NGC 7213

We report ALMA Cycle 1 observations of CO(2-1) at 229.2 GHz of NGC 7213, an early-type SA(s)a galaxy harboring a Seyfert 1/LINER. Previous neutral and ionized gas observations suggest the presence of a warped gaseous disk that could be the result of a merger. It presents a giant H$\alpha$ filament and two HI tidal tails, confirming to be a highly disturbed interaction system (Hameed et al., 2001). Stellar kinematics is dominated by non-circular motions, along two spiral arms (Schnorr-Müller et al., 2014). In the central ~3 kpc, the CO map reveals a a widely distributed multiple-arm spiral structure, tracing the dusty spiral arms, as can be seen in the HST image (**Figure 1**). There is an offset peak located at 200 pc north from the center, meaning that the peak of the CO emission is not concentrated in the very center.

In general, the velocity field in the left panel of **Figure 2** is well-described by rotation, presenting some slightly perturbations along the minor axis (at $10''$) probably due to streaming motions from the spiral arms. By applying the Bertola et al. (1991) model to generate a 2-D velocity model that minimizes the residuals, we find that the position angle is $-18^\circ$ and the systemic velocity should be corrected in 30 km/s. The residuals do not indicate hints of a significant blue and/or red-shifted components and this result indicates that probably there is no molecular outflow in NGC 7213.

### 3.2. NGC 1808

The "hot spot" galaxy NGC 1808 is remarkable for its very dusty appearance and especially for its well-known system of dark radial filaments. NGC 1808 is a Starburst/Seyfert 2 galaxy located at 9.1 Mpc and it is classified as a SAB(s)a. Accordingly to Reif et al. (1982), it has an inclination of $57^\circ$. Atomic gas traced with H I is concentrated in the galactic bar, disk, and a warped outer ring, indicating a tidal interaction in the past with the neighbor galaxy NGC 1792 (Koribalski et al., 1996). It presents prominent polar dust lanes and gas outflow emerging from the nucleus, as revealed in optical studies that indicate an outflow of dust and neutral and ionized gas (as seen in H$\alpha$, [N II], Na I D, and H I by Koribalski et al., 1993; Phillips, 1993). In particular, Na I D is seen blueshifted in absorption and redshifted in emission and *B-R* images show that the dust plumes associated with the outflow reach ~3 kpc above the plane. Near-infrared integral-field spectroscopy with SINFONI by Busch et al. (2017) showed a large gas reservoir and a disturbed gas velocity field that shows signs of inflowing streaming motion in the central ~100 pc.

We report ALMA Cycle 3 observations of CO(3-2), CS(7-6), HCN(4-3), and $HCO^+$(4-3) in band 7 with a resolution of $0.27''$. **Figure 3** shows that the CO emission follows the star-forming central 500 pc ring and the very center has a spiral trailing structure, that is also observed in CS, HCN, and $HCO^+$.

From the velocity map in **Figure 4**, the dominant velocity feature appears to be due to circular rotation in the disk. After subtracting a model for the velocity field by Bertola et al. (1991), we do not find significant patterns in the residuals and if there is a presence of an molecular outflow in the galaxy, it will be difficult to disentangle from the dominant circular motion in the 1st moment distribution. We need to explore in details the position-velocity diagrams along the dust lanes observed in the HST images. Additionally, Salak et al. (2016) presented evidence of a molecular gas outflow seen in CO(1-0) from the nuclear starburst region ($r \lesssim 250$ pc) that could be only detected in the position-velocity diagram. The outflow has a maximum velocity of $\upsilon_{out}$ ~180 km/s and mass outflow rate between 1 and 10 $M_\odot$/year, comparable to the total star formation rate in the starburst 500 pc region, that corresponds to SFR $\sim 5M_\odot$/year in the "hot spots." The kinematics of our CO(3-2) observations

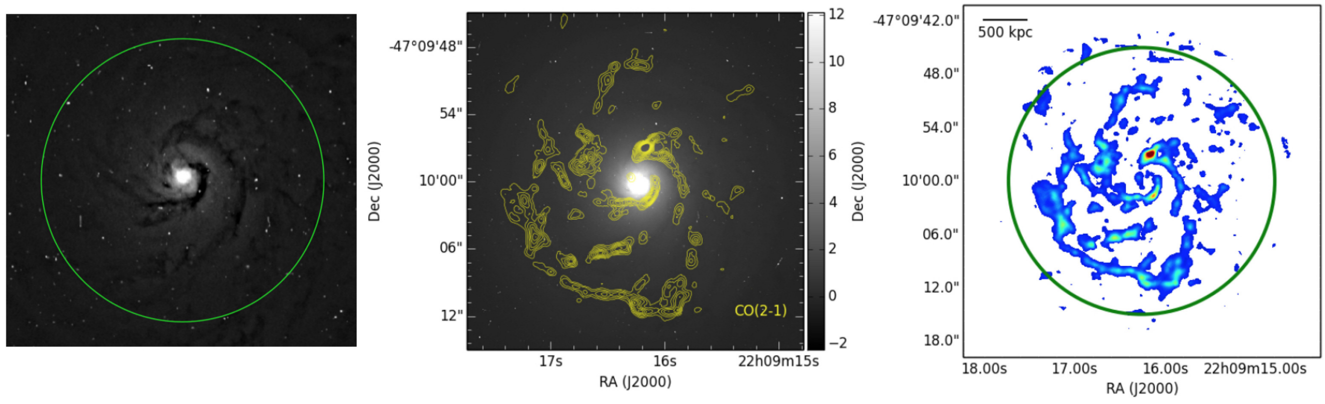


**FIGURE 1 |** In the left and middle panels we show an unsharp-masked F606W HST image and the original image with CO(2-1) contours overlaid, respectively. Right: CO(2-1) intensity map of NGC 7213 clipped at $>5\sigma$. The green circle represents a 30″ diameter.

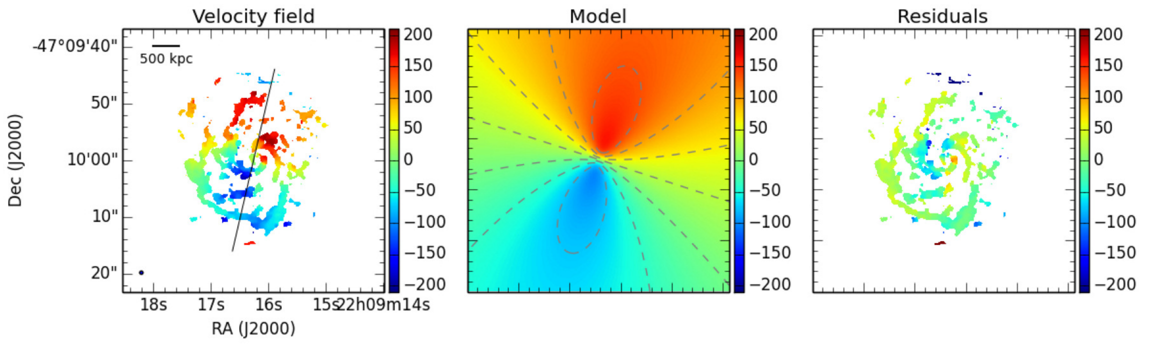


**FIGURE 2 |** Left: Velocity map of NGC 7213 clipped at $>5\sigma$. In the middle panel the best fit model using the Bertola et al. (1991) function and the residuals, after subtracting the model from the data, are shown on the right.

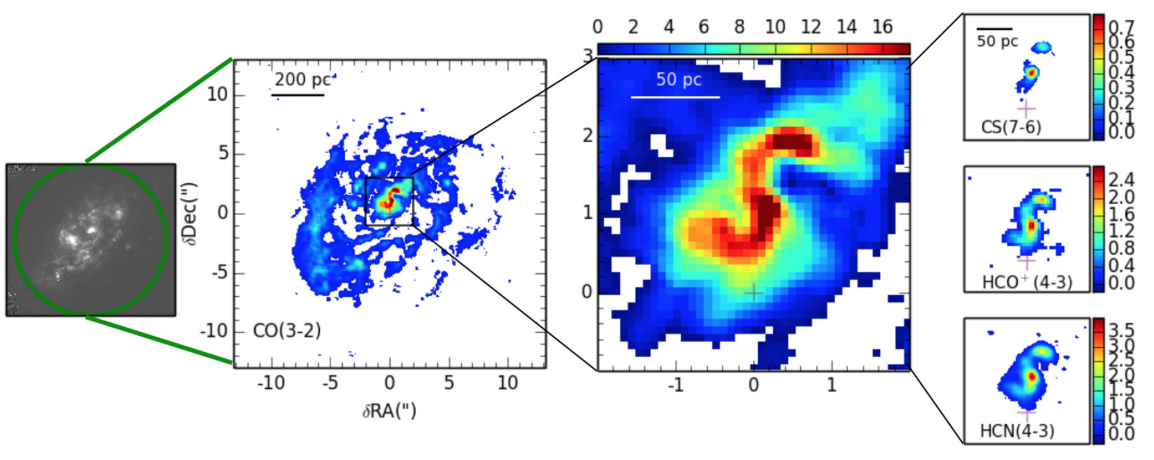


**FIGURE 3 |** From the left to the right panels: a WFC/F658N HST image followed by the 26″ diameter imaged area of CO(3-2) observations with ALMA. The next panels shows a zoom of the spiral trailing structure observed, and the subsequent plots show the same detection as seen in CS(7-6), $HCO^+$(4-3), and HCN(4-3). All the intensity maps were clipped at $>5\sigma$.

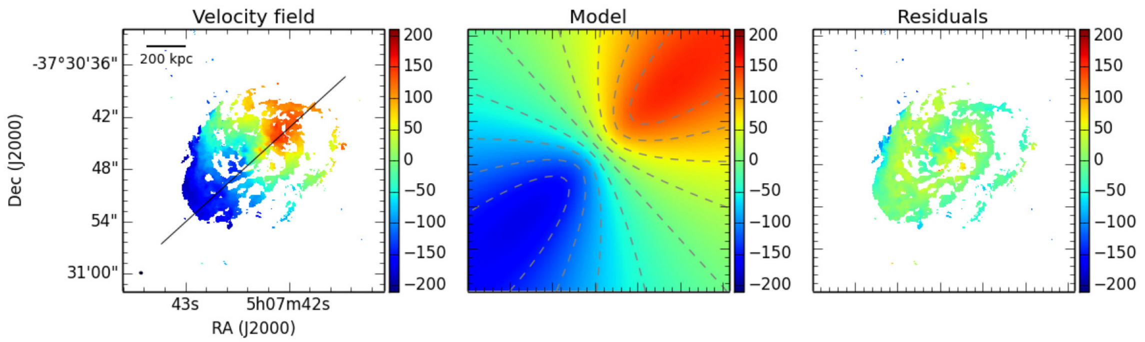


**FIGURE 4 |** Left: Velocity map of NGC 1808 clipped at $>5\sigma$. In the middle panel the best fit model using the Bertola et al. (1991) function and the residuals, after subtracting the model from the data, are shown on the right.

do not show strong outflows at this scale. Certainly, the outflow is more significant at larger scales. A further analysis of the molecular gas and the outflow in NGC 1808 will be present in a forthcoming paper (Audibert et al., in preparation).

## 4. PERSPECTIVES

We are going to apply the same methodology to search for outflows and inflows in a modest sample of nearby Seyfert/LINERs galaxies that are part of a new ALMA follow-up of the—NUclei of GAlaxies (NuGa) project, a previous CO survey of low luminosity AGN performed with the IRAM PdBI. The new ALMA observations have the remarkable spatial resolution of ∼0.06–0.09″.

## AUTHOR CONTRIBUTIONS

AA has written the article; AA and FC have contributed to reduce the data; FC and SG-B have written the proposal; and all four authors have contributed to interpret the data and comment the paper.

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