The kinematics in the inner kiloparsec of nearby active galaxies as revealed by molecular (ALMA) and ionized gas (Gemini-GMOS/IFU)

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Resumen / Para trazar flujos entrantes y salientes nucleares en AGNs, determinar la masa del gas involucrado y su impacto en la galaxia huésped y el agujero negro nuclear, se requieren de estudios en imágenes en 3-D tanto del gas ionizado como del molecular. Nuestro objetivo es mapear la distribución y cinemática del gas molecular e ionizado en una muestra de galaxias activas, para cuantificar los flujos entrantes y salientes nucleares. Aquí, analizamos la cinemática nuclear en la región de 1 kpc más interno de una submuestra de tres galaxias Seyfert cercanas por medio de: observaciones con ALMA de la emisión de CO J : 2–1 a resolución espacial de 0.5″ y $\sim$2.6 km s^{-1} de resolución espectral (NGC 1566), y observaciones por Gemini-GMOS/IFU de líneas de emisión de gas ionizado a similar resolución espacial (UGC 2024 y ESO 362–G18). Mientras el gas molecular como el ionizado muestran signos de rotación, existen movimientos no circulares significativos en el kiloparsec central de las tres fuentes. En NGC 1566, por ejemplo, existen movimientos no circulares en el 200 pc más interno, mientras lóbulos con corrimiento al azul y al rojo prominentes ($\sim$80 km s^{-1}) son encontrados a lo largo del eje menor en las zonas más internas lo que interpretamos como la presencia de un flujo saliente molecular en el disco con velocidades reales de $\sim$180 km s^{-1} en el núcleo y desacelerando a 0 a 1.5″ del núcleo ($\sim$72 pc). Este trabajo mostrará cómo las cinemática del gas perturbado en el kiloparsec central puede ser explicado de manera diferente y cómo los flujos salientes de gas molecular e ionizado parecen estar presentes con relativa frecuencia en galaxias activas cercanas en las escalas más internas.

Abstract / Tracing nuclear inflows and outflows in AGNs, determining the mass of gas involved in these, and their impact on the host galaxy and nuclear black hole, requires 3-D imaging studies of both the ionized and molecular gas. We aim to map the distribution and kinematics of molecular and ionized gas in a sample of active galaxies, to quantify the nuclear inflows and outflows. Here, we analyze the nuclear kinematics at the inner 1 kpc region of a subsample of three nearby Seyfert galaxies via: ALMA observations of the CO J : 2-1 emission at 0.5″ spatial and $\sim$2.6 km s^{-1} spectral resolution (NGC 1566), and Gemini-GMOS/IFU observations of ionized gas emission lines at similar spatial resolution (UGC 2024 y ESO 362–G18). While both ionized and molecular gas show rotation signatures, there are significant non-circular motions in the central kpc of the three sources. In NGC 1566 for example, there are non-circular motions in the innermost 200 pc, whereas prominent ($\sim$80 km s^{-1}) blue and redshifted lobes are found along the minor axis in the inner arcseconds which we interpreted as the presence of a molecular outflow in the disk with true velocities of $\sim$ 180 km s^{-1} in the nucleus and decelerating to 0 at 1.5″ from the nucleus ($\sim$72 pc). This work will show how the disturbed gas kinematics in the inner kpc can be differently explained and how molecular and ionized gas outflows seems to be present with relative frequency in nearby active galaxies at the innermost scales.

Keywords / galaxies: nuclei — galaxies: active — galaxies: Seyfert — galaxies: kinematics and dynamics

1. Introduction

A major topic of interest in extragalactic astronomy and cosmology these days is to understand the formation and evolution of galaxies. A primary question which the scientific community wants to address in this particular area is: How mass is transferred from galactic scales down to nuclear scales to feed the Super-Massive Black Hole (SMBH)? So far, the mechanisms regulating the transfer of material towards the galaxy core are still poorly understood. However, in recent years, this is becoming more accessible thanks to the recent and upcoming new generation of telescopes. One of the instruments, which is playing a main role, is the Atacama Large Millimeter/submillimeter Array (ALMA) which can provided us with better spatial and spectral resolution. We are hence in the best epoch to study gas kinematics at high spatial resolution, covering almost the entire electromagnetic spectrum. One of the most attractive targets are active galaxies such as Seyferts, which have the potential to heats or disrupts the gas, and hence slows down star formation through feeding/feedback processes.

Previous studies have pointed out that a triggering mechanism which can start the nuclear activity are dusty nuclear spirals. Martini et al. (2003) show that nuclear dusty spirals occur with comparable frequency in both active and inactive galaxies. The only difference is that none of the AGNs lack this structure implying that nuclear dusty spirals are correlated with AGNs. Following this issue, Simões Lopes et al. (2007) studied a sample of normal and active galaxies and showed that dusty nuclear spirals are present in 100 % of early type AGNs whereas in only 25 % in non-AGNs. More recent studies from optical spectra of several nearby Seyferts with Integral Field Units (IFUs) have demonstrated that gas inflows are present along these dusty spirals in the inner kiloparsec (e.g.: Schnorr-Müller et al., 2014a,b). These evidences, along with the frequency detected of dusty spirals, support the hypothesis that nuclear spirals are one of the most important mechanism for fueling the SMBH, transporting gas from kiloparsec scales down to within a few tens of parsecs of the active nucleus. Several authors who follow this argument, have tried to quantify this inflows at the inner scales in nearby AGNs with optical and near-infrared observations (e.g.: Storchi-Bergmann et al., 2007; Riffel et al., 2008; Schnorr-Müller et al., 2014a,b, 2017b,a). They obtained inflow velocities ranging between 50 – 200 km s^{-1} as well as mass inflows rates around 0.1 – 1 $M_{\odot}$ yr^{-1}. The most accepted interpretation of the small values of mass inflow rates do not agree with the expected ones, which is necessary to initiate a nuclear activity in galaxies, is that at frequencies close to the optical band, we are able to observe only the hot skin of a much larger gas reservoir and flow, which should otherwise be dominated by cold molecular gas (e.g. CO). For this, our immediate goal is to map both the spatial distribution and kinematics of cold molecular gas in order to quantify the actual inflows/outflows at the same scale probed by the optical and near-IR observations. Some of the most recent results obtained so far, following this goal by our group, are shown in the next section.

2. Results

We have noted that outflows in nearby Seyfert galaxies are present with noticeable recurrence in the inner kiloparsec as ionized and molecular gas. Particularly, Muñoz et al. (in prep.), have detected non circular features in the central region of the Seyfert galaxy UGC 2024, interpreting this as a nuclear outflow of ionized gas. Spectra analysis of its ionized line emissions as [O III], [N II] and H_{α} observed by GMOS/IFU (see Fig. 1) show that emission lines of ionized gas lie at zero velocities at several orientations especially in [O III], postulating this scenario as concrete evidence of a spherical outflow at lower dust extinction: with the presence of dust (dominantly in the plane of the galaxy disk) we would preferably see emission from the hemisphere in front of the galaxy and moving towards us, i.e., blueshifted radial velocities. In the absence of dust one would expect a high dispersion and a median velocity close to systemic which is the case here (6790 km s^{-1}). The outflow velocity estimated was $v = 250$ km s^{-1} which was lower than the escape velocity estimated (300 km s^{-1}) indicating that this expanding sphere of ionized gas is not going out of the galaxy, rather it is slowing down until finally it goes back to the galactic nucleus. Analogous results were found in the nearby Seyfert galaxy ESO 153–G20 (Soto-Pinto et al., in prep.)

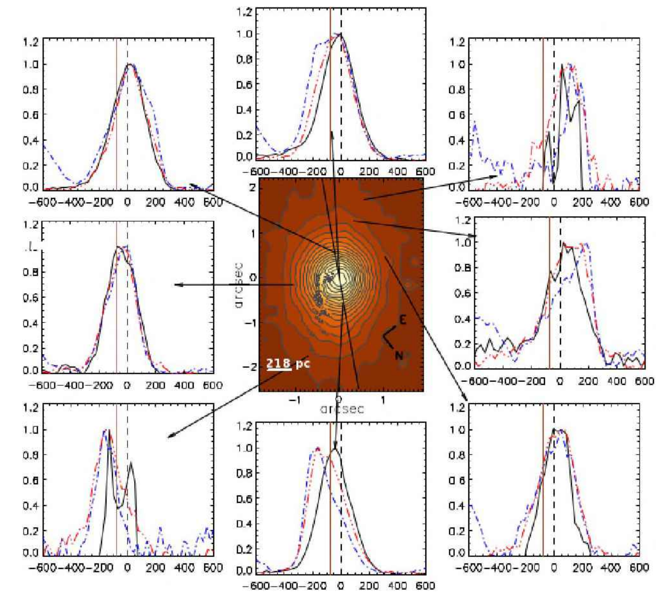

Figure 1: Line profiles in UGC 2024 of the [O III] (solid black), [N II] (triple dot-dashed red) and H_{α} (dot-dashed blue) emission lines extracted from 0.16″ radius apertures centered on the offset positions (in arcsec) indicated in each panel. The offsets are calculated from the stellar continuum peak. The central panel shows the stellar continuum flux in greyscale and contours, and the major axis as a solid black line: it is shown to illustrate the locations of the individual apertures. For easy comparison, the profiles are normalized and each panel indicates the systemic velocity (dashed black line) and the velocity expected from the best-fit H_{α} Bertola rotation model (solid brown line). The x-axis is in km s^{-1} centered on the systemic velocity.

Another study of the ionized gas was presented in Humire et al. (2018) for the Seyfert galaxy ESO 362–G18 also with GMOS/IFU. They have reported non-circular features related to an outflow in [O III]. Based on this, they proposed a toy model to explain why [O III] is preferentially redshifted to our line of sight (LOS), except at the nucleus where is blueshifted (see top panel

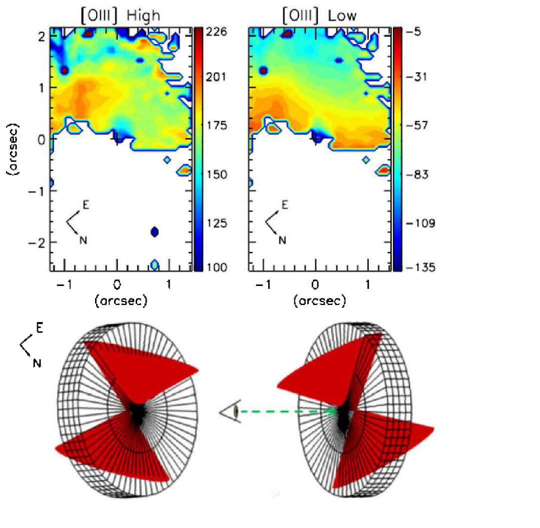

Figure 2: Top panel: Results of the double component fit in ESO 362-G18 to the [O III]. Velocity fields of the high-velocity and low-velocity narrow components. Bottom panel: Proposed configuration for the nuclear region of ESO 362–G18, where the galactic disk is shown both from our perspective (left; in the same orientation as the data cube) and in profile (right). (Source: Humire et al., 2018).

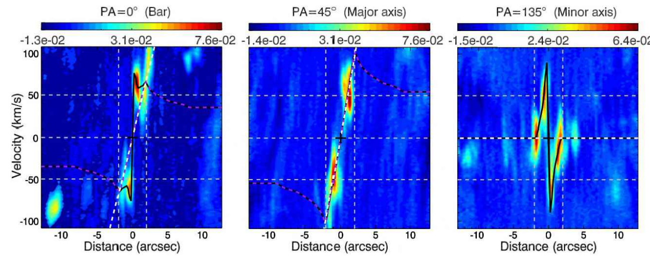

Figure 3: Position-Velocity diagrams of the CO J : 2-1 emission in NGC 1566 along three PAs are shown in color following the color bar above each panel. The PA of the "slit" over which the pv diagram was extracted is indicated above each panel, as are the PAs corresponding to the large-scale bar (left), major (middle) and minor (right) axis of the galaxy. On the x-axis, the linear scale corresponds to 48 pc arcsec^{-1}. Negative offsets correspond to the PA listed above the panel, i.e., positive offsets are along the 180° plus the listed PA. The black cross indicates the position of the 230 GHz continuum peak (presumed to be the galaxy center). The dashed white and purple lines are rotation models (see Slater et al. (2019) for details). The solid black line shows the expectation of adding our outflow model (see Slater et al. (2019) for details). (Source: Slater et al., 2019).

of Fig. 2). The best interpretation was the presence of a biconical outflow of ionized gas in the nuclear region which was modeled as shown in the bottom panel of Fig. 2. The top ionization cone intersects the galaxy disk behind the plane of the sky, generating the redshifted component of [O III] in the high velocity component noted in the top panel of Fig. 2. This cone also intersects the galaxy disk in front of the plane of the sky, but only in a very small region close to the nucleus, producing the greatest blueshift seen in the low-velocity component of [O III] (top panel of Fig. 2). The bottom ionization cone is almost always hidden by the galactic disk.

For NGC 1566, Slater et al. (2019) show, with respect to cold molecular gas, a significant outflow of CO in the nuclear region. However the outflow possibility was neglected by Combes et al. (2014) and supported later with optical observations with SINFONI in Smajić et al. (2015). Non circular features were detected for CO J : 3-2 observations of NGC 1566 using ALMA in Cycle 0 (Combes et al., 2014), however they reported no outflow arguing small amplitude owing to streamings by the large-scale bar. In spite of this, we defend an outflow scenario with one of the most significant evidence being illustrated in Fig. 3. On these, the Position-Velocity diagram of CO data along the minor axis not only shows the high velocity components, but also lower brightness emission which connects these high velocity components to the zero velocity components seen at $r \approx 1.8''$ from the nucleus. These diagrams also show velocity deviations which are consistent with a radial cold molecular outflow in the plane of the disk at different position angles (PAs) (more details in Slater et al. (2019).

3. Conclusions

It has been demonstrated that the feedback processes as nuclear outflows take part at different phases of the gas (ionized gas and cold molecular gas) with presumably the same origin but are morphologically different. Thus it is important to elucidate these components not only from one wavelength range, but also by taking multi-wavelengths observations in order to get the full picture of their physical properties, and here is where the new generations of detectors, telescopes as well as new interferometric techniques will play an important role to achieve this goal in the coming years.

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