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IMAGING SPECTROSCOPY OF THE CENTERS OF NEARBY AGN: MOLECULAR GAS STREAMING AND OBSCURING THE ACTIVE NUCLEUS OF NGC 1068

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RESUMEN

Alcanzando resoluciones espaciales hasta de 0.075″, hemos obtenido imágenes de la distribución y cinemática del gas y las estrellas de un conjunto de AGN cercanos utilizando el espectrógrafo de campo integral asistido por óptica adaptativa SINFONI en el infrarrojo cercano. Presentamos los resultados sobre las propiedades generales del proceso de formación de estrellas y el gas molecular en las regiones centrales de 9 AGN. Adicionalmente, en NGC 1068 con una resolución de 5 pc hemos observado gas molecular exactamente enfrente del AGN y fluyendo hacia el núcleo. Interpretamos este cúmulo nuclear de gas como un conjunto de nubes cayendo hacia el núcleo y que forman la parte externa y ópticamente gruesa de una estructura amorfa y grumosa de polvo/gas molecular.

ABSTRACT

At spatial resolutions as small as 0.075″, we have mapped the distribution and kinematics of the gas and stars in a survey of nearby AGN using the near infrared adaptive optics integral field spectrograph SINFONI. Here we present results on general properties of the star formation and the molecular gas in the central regions of 9 AGN. In addition, for NGC 1068 at a resolution of 5 pc, we present direct observations of molecular gas right infront of the AGN and streaming towards the nucleus. We interpret the nuclear clump of gas as a set of infalling clouds that form the optically thick outerpart of an amorphous clumpy molecular/dusty structure.

Key Words: galaxies: active — galaxies: nuclei — galaxies: Seyfert — infrared: galaxies

1. INTRODUCTION

The coexistence of an active nucleus and a starburst region on scales of a few parsecs around the centers of Seyfert galaxies, is one of the key issues to investigate in the context of AGN. Increasing evidence that starbursts do occur in the vicinity of AGN has revived the importance of disentangling how AGN and star formation activity impact on each other. Additionally, a fundamental prediction of the unified model is the existence of a torus of gas and dust surrounding a supermassive black hole. In order to help elucidate the discussion on these topics, we have undertaken a research program based on SINFONI imaging spectroscopy at near-IR wavelengths, which primary goals are to: (i) determine the extent and history of star formation, and its relation to the AGN; (ii) measure the properties of the molecular gas, and understand its relation to the torus; (iii) derive black hole masses from spatially resolved stellar kinematics. We have observed Seyfert galaxies, of which 2 are ULIRGs and 1 a QSO, which contain supermassive black holes of 10 to $100\times10^6\ M_\odot$. Here we present results on general properties of the star formation (Davies et al. 2007), the molecular gas (Hicks et al. in prep), and 2 important features of the H_2 in NGC1068 (Müller Sánchez et al., in prep).

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2. NUCLEAR STAR FORMATION IN AGN

Although our AGN sample is rather heterogeneous, we have analysed them in a consistent manner to derive: the stellar K-band luminosity, the dynamical mass, the equivalent width of the Brγ line, and the supernova rate. We have used these as diagnostics to constrain STARS evolutionary synthesis models and hence characterize the star formation timescales and ages of the starbursts close around each AGN.

Our survey provides strong evidence for recent star formation in the last 10–300 Myr at scales of less than 50 pc from the nucleus. The star formation timescale is short, of order 10 Myr. While the starbursts were active, they would have been Eddington limited and their star formation rates would have been much higher than the current ones. Due to this very high star forming efficiency, the starbursts would have also exhausted their fuel supply on a short timescale and hence have been short-lived.

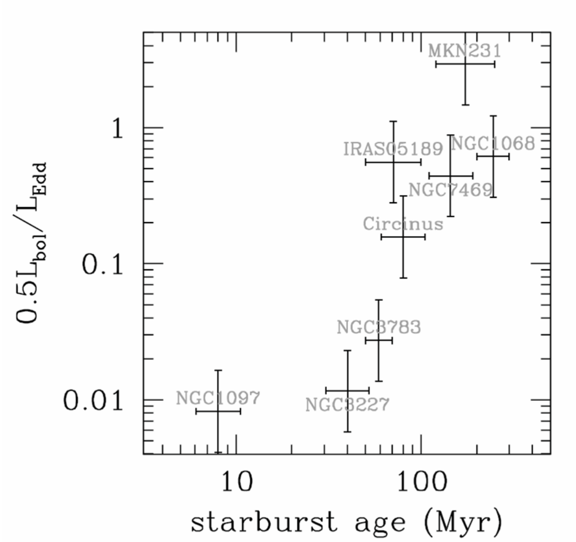

Fig. 1. Relationship between the luminosity of an AGN and the age of the most recent episode of nuclear star formation. The luminosity is shown with respect to the Eddington luminosity of the black hole.

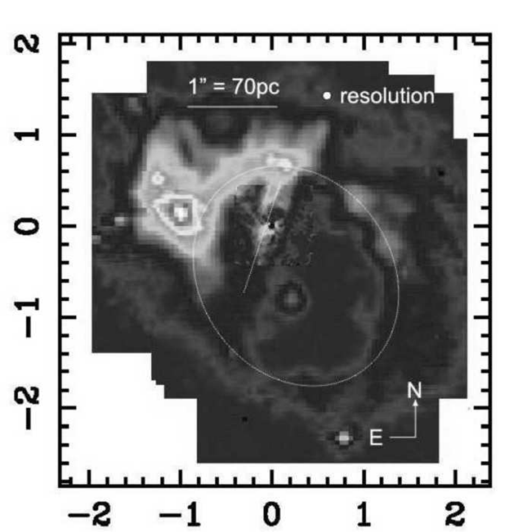

Fig. 2. SINFONI H_2 10S(1) flux map of the central $4'' \times 4''$ of NGC 1068.

It therefore seems likely that nuclear starbursts are episodic in nature. Given that the star formation occurs on scales of < 50 pc, it is inevitable that it and the AGN will have some mutual influence on each other. Our data hint at a possible relationship between the characteristic age of the star formation and the accretion rate onto the AGN. The AGN which are radiating at lower efficiency $< 0.1\ L/L_{\rm Edd}$ are associated with starbursts younger than 50–100 Myr; AGN that are accreting and radiating more efficiently $> 0.1\ L/L_{\rm Edd}$ have starbursts older than 50–100 Myr (Figure 1). This implies that there could be a delay between starburst activity and AGN activity. Indeed, there appears to be a delay of 50–100 Myr between the onset of star formation and the onset of AGN activity. We have interpreted this as indicating that fuelling a supermassive black hole requires the presence of a starburst.

3. MOLECULAR GAS IN AGN

Our survey of nine nearby AGN shows that the distribution and kinematics of the nuclear molecular hydrogen is consistent with an optically thick molecular/dust structure surrounding the AGN such as those invoked in obscuring torus models. Evidence supporting this includes fits to the flux distributions, which indicate that the molecular gas is in a disk-like structure with size scales of 10–60 pc, consistent with model predictions of 10–100 pc (Hönig et al. 2006). In addition, the gas column density at these same radii, estimated to be at least 10^{23} cm^{-2}, is high enough to provide the needed obscuration of the AGN (Bassani et al. 1999). Furthermore, the bulk of the molecular hydrogen in these galaxies shows ordered rotation, but with relatively high velocity dispersions of 70–130 km s^{-1}. On scales less than 50 pc the velocity dispersion is greater than, or comparable to, the rotational velocity (i.e. $V_{\rm rot}/\sigma \sim 1$), implying that the gas is geometrically thick with respect to the radial scales. Moreover, the molecular gas is similar in both distribution and kinematics to the nuclear stellar disks suggesting that the torus is composed of a mixture of molecular gas and stars.

4. NGC 1068

The molecular hydrogen emission at scales of few arcseconds from the nucleus has been mapped previously reaching spatial resolutions down to $\approx 0.5''$ (Galliano & Alloin 2002). Our SINFONI data at these scales reach $\sim 0.1''$ resolution and reveal a complex distribution of the gas which has not been entirely observed before (Schinnerer et al. 2000). As can be seen in Figure 2, besides the bright emission east of the AGN there are several prominent regions of H_2 emission which include among others an expanding ring of 150 km s^{-1} that is centered $0.6''$ southwest of the AGN, an isolated knot of emission $1''$ south of the AGN, and a linear structure leading to the AGN from the north and south. The morphology of the H_2 1-0S(1) emission in the central 0.8 arcsec^2 of NGC 1068 with a resolution of $0.075''$ ($\sim$5 pc) is presented in Figure 3. The peak of the 2.1 μm non-stellar continuum at these scales is located at the origin of the image and is represented by a cross. This is well identified as the position of the

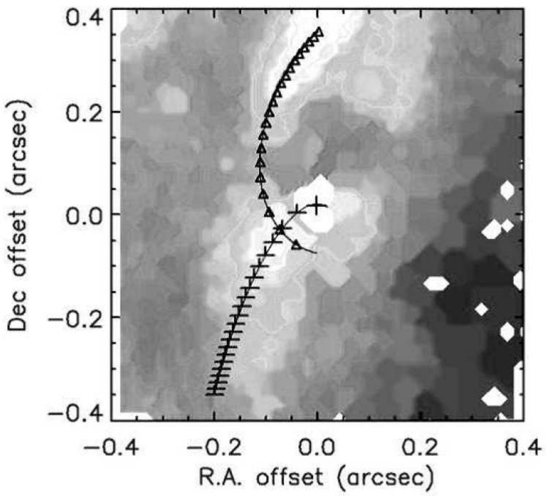

Fig. 3. Flux map of the H_2 emission in the central 0.8 arcsec^2 of NGC 1068. The image is binned using Voronoi tessellations. The open triangles show the projected trajectory of the northern finger of gas. The half-crosses show the past trajectory of the gas which is currently located in front of the AGN.

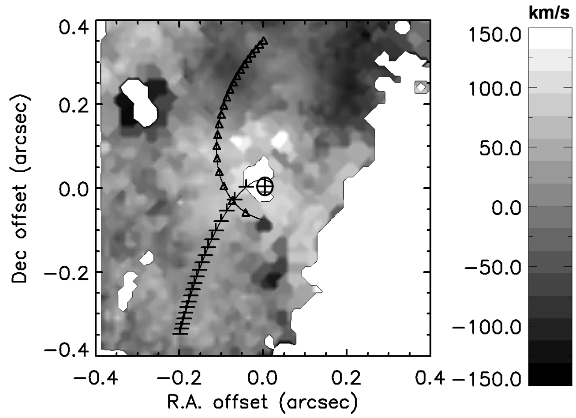

Fig. 4. Velocity map of the H_2 emission in the central 0.8 arcsec^2 of NGC 1068. The rejected pixels are those with a flux density lower than 10% of the peak of the central emission shown in Figure 3.

central engine. As can be seen in Figure 3, the linear feature includes a brighter region on a scale of 10 pc coincident with the AGN, which we interpret as a direct view of the gas obscuring the nucleus in this galaxy.

Remarkably, however, the motions of both this central structure and that to the north indicate that the gas is streaming almost directly towards the nucleus rather than orbiting it on circular paths (see Figure 4). Given its current position and velocity, the northern knot of gas will pass very close to the nucleus within a few Myr. On the other hand, the velocity of the gas that is now lying in front of the nucleus suggests that over the last few Myr it has fallen in along the southern extension of the linear feature. The trajectories of these streamers are plotted over the flux and velocity maps in Figures 3 and 4. These motions are strong evidence that we are seeing, on scales down to a few parsec, how gas is being driven toward the AGN in NGC 1068, and hence how the AGN is being fuelled.

The mass accretion rate to ∼1 pc from the AGN can be estimated assuming that material falls down into the nucleus through the linear structure. We have used the conversion factor found by Müller Sánchez et al. (2006) to estimate the total gas mass of the northern cloud from its $L_{1-0\mathrm{S}(1)}$ and obtained a value of $6\times10^7\ M_\odot$ for $L_{1-0\mathrm{S}(1)} \sim 16000 L_\odot$. The inflow time scale is obtained directly from the modelling and has a value of 2 Myr. This factor and the total gas mass yield a mass accretion rate at these scales of $\sim 30\ M_\odot\ \mathrm{yr}^{-1}$. Finally, our observations at these scales suggest that the nuclear clump of gas can be associated with the obscuring material that is hiding the nucleus but not in the classical picture of a rotating torus. This scenario is mainly ruled out by the kinematics which do not show any type of rotation near the AGN. Hence we interpret this nuclear knot of gas as an infalling cloud, or most probable a set of clouds, that form the optically thick outer-part of an amorphous clumpy molecular/dusty structure and enclose smaller clouds, qualitatively similar to a nested tori scenario (Bannikova & Kontorovich 2007). Nevertheless, based on the morphology and kinematics of the gas, we can state that if there is a rotating torus in NGC 1068, its outer radius R_{out} has to be smaller than 10 pc and it is enclosed by this AMDO (Amorphous Molecular/Dust Obscuration).

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