GNIRS NIR Integral Field Spectroscopy of NGC 5128

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Resumen / Presentamos observaciones del núcleo de NGC 5128 obtenidas con la unidad de campo integral disponible en GNIRS hasta 2007. Este es el núcleo activo más cercano, y está oculto para el rango espectral óptico debido a la presencia de una gruesa banda de polvo. La espectroscopía en banda K ($1.9 - 2.55\,\mu$m) permitió penetrar el velo de polvo y obtener algunos resultados preliminares que se presentan en este trabajo. Incluimos una nueva determinación de la masa del agujero negro central, y un mapeo preliminar de la emisión del gas molecular, con una resolución espacial de ≈ 7 pc. Este trabajo nos permite explorar el potencial de este tipo de capacidad observacional en GNIRS, pues como parte de su programa de mejoras instrumentales, Gemini está construyendo dos unidades de campo integral para el espectrógrafo infrarrojo GNIRS que estarán disponibles a fin de 2021. Una de las unidades operará en modo de *seeing* natural, permitiendo observar un campo de $3.2'' \times 4.8''$ muestreado cada $0.15''$ con una resolución espectral $R \approx 7200$ en el rango espectral $0.9 - 5.4$ μm. La otra unidad operará en complemento con la óptica adaptativa de Gemini Norte permitiendo muestrear cada $0.05''$ un campo de $1.25'' \times 1.8''$, con $R \approx 18000$, una resolución espectral inédita para este tipo de espectroscopía de campo integral infrarroja.

Abstract / We present observations of the active nucleus of NGC 5128 obtained with the integral field unit (IFU) available at GNIRS spectrograph until 2007. This is the nearest AGN and is completely hidden to the optical range by a strong dust lane due to the edge-on orientation of the galaxy disk. The K-band ($1.9 - 2.55\,\mu$m) IFU spectra uncovered the nuclear emission and allowed a new determination of the supermassive black hole mass, plus mapping the molecular gas with a spatial resolution of ≈ 7 pc. This work allows us to explore the scientific potential of the integral field capabilities in GNIRS, considering that Gemini is upgrading the instrument with the addition of two IFUs working in the spectral range $0.9 - 5.4$ μm, which will be available by the end of 2021. One of the IFUs will operate under natural seeing, allowing a field of $3.2'' \times 4.8''$ sampled each $0.15''$ with a spectral resolution $R \approx 7200$. The other unit will complement Gemini North adaptive optics system, sampling each $0.05''$ a field of $1.25'' \times 1.8''$, with $R \approx 18000$, an unprecedented spectral resolution for this kind of NIR integral field spectroscopy facility.

Keywords / galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics — galaxies: individual (NGC 5128) — quasars: supermassive black holes — techniques: imaging spectroscopy

1. The nucleus

NGC 5128 hosts one of the nearest active galactic nuclei (AGN), which is the source of the great radiosource Centaurus A. Using Cepheid variables, Ferrarese et al. (2007) determined a distance of (3.42 ± 0.12) Mpc, giving a scale of 0.17 kpc arcsec^{-1}. In spite of its relative proximity, the nucleus is not observable in optical wavelengths (Figure 1). In similar scenarios, the nuclear region kinematics can be studied successfully at near-infrared (NIR) wavelengths to uncover unexpectedly complex dynamical systems as the double nucleus in NGC 5236 (Díaz et al., 2006), or the hidden nuclear source of the galactic wind in NGC 253 (Günthardt et al., 2019). In NGC 5128, Schreier et al. (1998) discovered a 40 pc diameter central disk in the Paα NICMOS/HST images. Subsequent works have demonstrated that the gas kinematics appears complex even at wavelengths in the $1 - 2$ μm spectral range (Marconi et al., 2006; Häring-Neumayer et al., 2006; Cappellari et al., 2009). There are few estimates of the nucleus mass distribution and, in particular, the supermassive black hole (SMBH) mass determinations have significant dispersion, ranging from $1{\times}10^7$ to $3{\times}10^8$ M$_\odot$ (see Gnerucci et al., 2011, and references therein). This motivated us to use unpublished $1.9 - 2.55$ μm integral field spectroscopy observations to contribute with an independent mapping of the molecular gas emission and another determination of the SMBH mass.

2. The instrument and the observations

The Gemini Near-Infrared Spectrograph (GNIRS) (Elias et al., 2006) started to operate in the Gemini South Telescope in 2004, and since 2010 operates in Gemini North, offering a variety of spectroscopic capabilities in the spectral range $1 - 5$ μm. Until 2007, it had an Integral Field Unit (IFU) with a field of $3.2'' \times 4.8''$

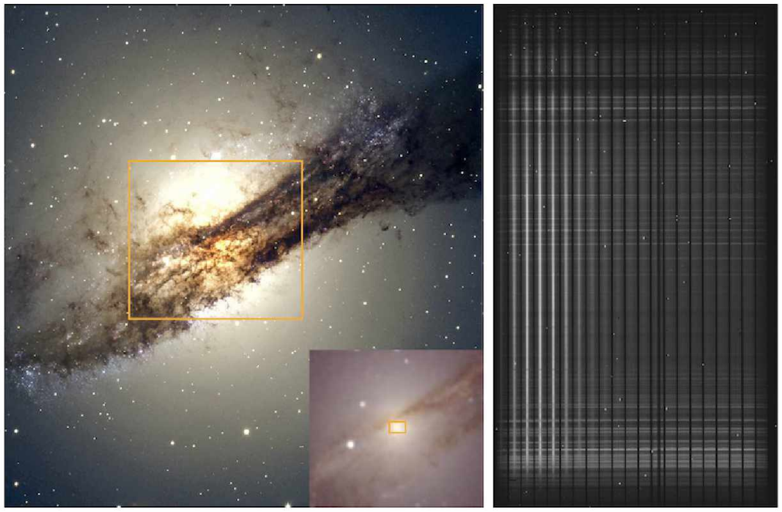

Figure 1: *Left panel:* BVR image obtained with FORS2/VLT (ESO PR0005, licensed under a Creative Commons Attribution 4.0 International License). The inset shows the 2MASS $JHKs$ image, which shows the nucleus through the central dust lane. The smallest rectangle depicts the GNIRS IFU field of view ($3.2'' \times 4.8''$). North is up and east is left. *Right panel:* Part of the two-dimensional frame showing the pseudo-slit arrangement in the spatial (horizontal) direction, and each $0.15''$ spaxel spectrum dispersed in the vertical direction.

divided in 21 slices of $0.15''$ width, with reflective optics that reorder the slices with anamorphic magnification into a pseudo-longslit and a spatial sampling of $0.15''$ pixel^{-1}. The observations we present here were taken in 2005, covering two dithered positions in the central region of NGC 5128. The observed spectral range was the K-band ($1.9 - 2.55$ μm), with spectral resolution $R \approx 1700$ and a spatial resolution $\approx 0.4''$ in 2.2 μm. Sky, arc, flats and early type telluric standard stars were also observed. A standard data reduction process was performed with the Gemini IRAF/PYRAF package following the "GNIRS Examples" recipe.

3. First Results

Figure 2 shows the 2.3 μm continuum emission map, with the active nucleus appearing as a compact object with a FWHM $< 0.4''$, surrounded by an extended disk-like component which we intend to quantify in the future work. It is worth noting that the galactic core is usually not observed as clearly resolved as in the present work, because of the contribution of the nebular emission in the broad band imaging. The Brγ emission is strongly concentrated on the nucleus and appears elongated in the direction of the large scale radio jet (PA $\approx 130°$), while the molecular emission is more intense in an annular region at an average radius of $0.9''$, respect to the spaxel with the continuum peak, which we take as the nucleus position.

An interesting feature, reported by other authors too (e.g. Krajnović et al., 2007), is that the ionized gas velocity field (as traced by the Brγ emission) has a high kinematic semi-amplitude (≈ 210 km s^{-1}) and a major axis PA rapidly changing with radius, due to the presence of the AGN jet and outflows. However, the molecular gas velocity field (Figure 2, H2 1-0S(1) at 2.12 μm) shows a cleaner rotational pattern with PA $\approx 20°$ and a semi-amplitude of 170 ± 15 km s^{-1} in the central $2''$, corresponding to a diameter of ≈ 34 pc. The molecular gas phase is dynamically cold and it is a good tracer of the disk kinematics in the central regions of galaxies (e.g. Gaspar et al., 2019). It indicates a mass of $(1.1{\pm}0.3){\times}10^8$ M$_\odot$/(sin i) in the central arcsecond of the galaxy. The most interior Keplerian mass value yielded by our data, at a resolved radius of $0.42''$ (≈ 7.1 pc) is $(1.3 \pm 0.2) \times 10^7$ M$_\odot$/(sin i).

This mass estimate is consistent with the lowest values found in the literature, for 8 measurements ranging from $1{\times}10^7$ to $3{\times}10^8$ M$_\odot$/(sin i) with spatial resolution better than $0.6''$ (see Neumayer, 2010). However, the molecular gas motion that we observe indicates that the SMBH mass is lower than the one expected for NGC 5128 galaxy luminosity and mass. Marconi & Hunt (2003) estimate $\approx 2.8 \times 10^8$ M$_\odot$ from the galaxy K-band total luminosity (M$_K = -24.5$, L$_K = 1.3{\times}10^{11}$ L$_{\odot K}$). Nevertheless, observational biases yield an intrinsic scatter of at least a factor of 2 in the mass values. These authors also found that the galaxy spheroid virial mass is correlated with SMBH mass. In that case, $M_{sph} = 3\ R_e \sigma_e^2\ G^{-1} = (5.6 \pm 1.5) \times 10^{10}$ M$_\odot$ yields a SMBH mass of $\approx 1.3 \times 10^8$ M$_\odot$ for NGC 5128. In summary, the SMBH mass as measured from the stellar dynamics seems to be much larger than the mass we measure from the molecular gas circular motion, leaving open the possibility that the central region structure of this galaxy merger is still rapidly evolving.

4. Future GNIRS IFUs

We plan to obtain the K-band spectra for a sample of nearby AGNs with apparent low mass SMBH in order to disentangle any bias in the determination of masses via the stellar and molecular gas kinematics. The work presented here also aims to demonstrate the GNIRS IFU

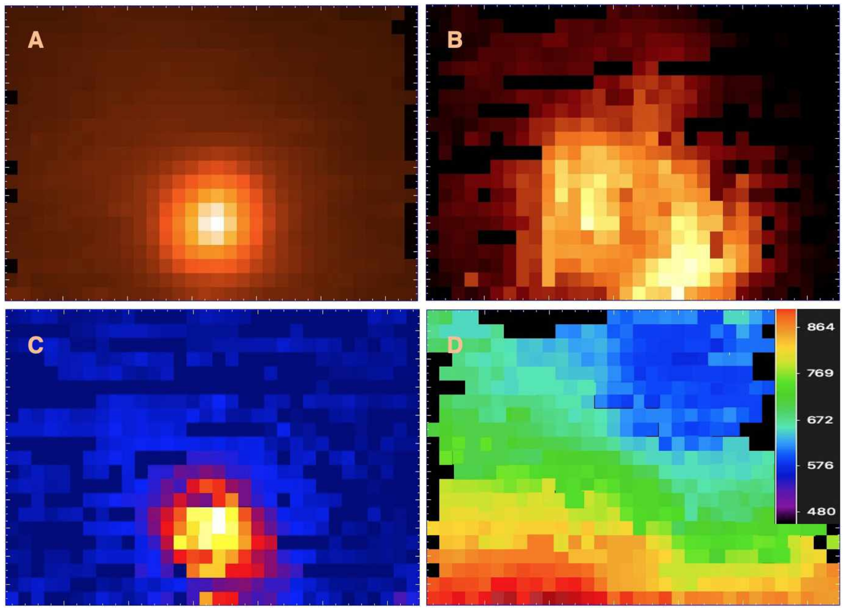

Figure 2: Example of GNIRS IFU observation of the NGC 5128 nucleus in the K-band, $3.2'' \times 4.8''$, *seeing* $< 0.4''$, $0.15''$ spaxels. Only spaxels with signal-to-noise level $S/N > 30$ are shown. North is down and east is left. *Panel A:* $2.3\,\mu$m pure continuum emission map. *Panel B:* H2 1-0S(1) molecular gas emission line at 2.12 μm. *Panel C:* Brγ ionized gas emission. *Panel D:* H2 1-0S(1) radial velocity field.

Table 1: IFUs currently available at GN and the future GNIRS IFUs.

Instrument / Mode	GMOS-N IFU-R	GMOS-N IFU	NIFS IFU	GNIRS LR-IFU	GNIRS HR-IFU
Spatial sampling $('')^2$	0.2×0.2	0.2×0.2	0.103×0.043	0.15×0.15	0.05×0.05
Sampled field $('')^2$	3.5×5	5×7	3×3	3.2×4.8	1.25×1.8
Spaxels	500	1000	2000	672	900
Max. spec. resolution	7100	7100	4500	7200	18000
Spectral range (μm)	$0.36 - 1.03$	$0.36 - 1.03$	$0.94 - 2.4$	$1.0 - 5.4$	$1.0 - 5.4$

capability, which was destroyed after an accident suffered by the instrument in 2007. As part of the Instrument Upgrade Program (Díaz et al., 2018), Gemini executes periodic public requests for proposals for small and medium size instrumentation projects. In 2018 Gemini awarded a proposal presented by Ray Sharples from Durham University, to build two new IFUs for GNIRS. One of them will reinstate the same capability as the one used in this work, with a large improvement in filling factor and throughput due to the recent advances in the techniques used to grind microscopic reflecting surfaces.

The second IFU represents a truly unique capability, considering that it will work with the Gemini North adaptive optics system (Altair), with a sampling of $0.05''$, spatial resolution better than $0.1''$ and a spectral resolution $R \approx 18\,000$ within the spectral range $0.9 - 5.5$ μm. The optical design has been presented by Calcines et al. (2020). Table 1 compares the integral field unit capabilities that will be available at Gemini North before the end of 2021, which will allow to explore several synergies, for example between the GMOS-N IFU-R and GNIRS LR-IFU modes.

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