Gemini/GMOS IFU stellar kinematics of the nuclear region of six nearby active galaxies

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ABSTRACT

We present two-dimensional (2D) mapping of the stellar velocity field within the inner 5′′ of six nearby active galaxies, using spectra obtained with the Integral Field Unit of the GMOS instrument at the Gemini North telescope. The sampling of the observations is 0′′.2, corresponding at the galaxies to spatial extents ranging from 10 to 30 pc. The spatial resolution range from 20 to about 180 pc, and the observed field of view covers a few hundred parsecs around the nuclei. The Calcium II triplet absorption features at \( \approx 8500 \AA \) were used to measure the stellar radial velocities and velocity dispersions. The radial velocity fields are dominated by rotation in all galaxies. A simple kinematical model assuming a purely rotating system with circular orbits in a plane was fitted to the radial velocity data. The turnover of the rotation curve is at only \( \approx 50 \) pc for NGC 4051 and between 200 and 700 pc for the other 5 galaxies. The velocity dispersion (\( \sigma \)) maps show the largest values (\( 100 \geq \sigma \geq 150 \) km s\(^{-1} \)) at the centre. In the cases of NGC 2273 and NGC 3227, there is a decrease to \( \sigma \approx 70 \)–80 km s\(^{-1} \) at \( \approx 200 \)–300 pc from the nucleus, delineating partial rings of low \( \sigma \) values. A similar broken ring seems to be present at \( \approx 400 \) pc from the nucleus also in NGC 4593. We interpret these low \( \sigma \) rings as traces of recently formed stars that partially keep the cold kinematics of the original gas from which they have formed. In NGC 3516 there is a decrease of \( \sigma \) outwards with the steepest gradient observed along the direction of the galaxy major axis, where \( \sigma \) reaches \( \approx 80 \)–90 km s\(^{-1} \) at \( \approx 400 \) pc from the nucleus.

The main novelty of the present work is the unprecedented spatial resolution reached by a 2D study of stellar kinematics of Seyfert galaxies using an IFU. The few similar IFU studies available in the literature for Seyfert galaxies have a much poorer spatial resolution and/or are restricted to the study of emission line kinematics.

Key words: galaxies: active – galaxies: Seyfert – galaxies: nuclei – galaxies: starburst – galaxies: kinematics and dynamics – stellar dynamics

1 INTRODUCTION

It is now widely accepted that active galactic nuclei (AGN) are powered by the accretion of material onto a central supermassive black-hole (SMBH). The present paradigm for the evolution of galaxies is that all galaxies which form bulges also form a SMBH at their centres (Ferrarese & Merritt 2000; Gebhardt et al. 2000). In this scenario, the active galaxies are those in which the SMBH is presently accreting material from its surroundings.

A problem still under investigation is the mechanisms by which the material is dragged to the nuclear regions to feed the AGN, as the galactic gas must lose almost all of its angular momentum in order to reach the central few parsecs. Signatures that such feeding is occurring include the frequent occurrence of recent star formation around AGN, which implies the existence of a gas reservoir close to the AGN (Schmitt et al. 1999; Cid Fernandes et al. 2000).
Besides the signatures of young stars observed in spectra of AGN, kiloparsec scale kinematic studies [Nelson & Whittle 1993; 1994] have suggested that Seyfert galaxies have lower mean mass-to-light ratios than normal galaxies, which also could be due to a younger near-nuclear stellar population (Oliva et al. 1993; 1994).

The presence of young stars near the nucleus seems also to be the explanation for the results of recent studies investigating the stellar kinematics on scales of hundred of parsecs [Emsellem et al. 2001; Garcia-Lorenzo et al. 1999; Marquez et al. 2003]. These studies have found a central drop in the stellar velocity dispersion (hereafter $\sigma$-drop) in a few galaxies with Seyfert nuclei. Wozniak et al. (2003) presented simulations showing that a new generation of stars formed at the centre of the galaxy from cold material would create such a drop which would remain visible for hundreds of Myrs. Nevertheless, a decrease in $\sigma$ towards the nucleus has been recently observed also in late-type non-active galaxies Ganda et al. (2003), supporting its link to recent star-formation, but not necessarily to nuclear activity in galaxies.

Most studies available in the literature on kinematics of Seyfert galaxies are based on long-slit observations, which are restricted to only one axis of the host galaxies. In order to properly probe the galactic gravitational potential, as well as to investigate the nature and extent of the $\sigma$-drops, it is necessary to cover a 2D region, what we have done in the present work using the Integral Field Unit (IFU) of the Gemini Multi-object Spectrograph (GMOS).

The power of IFU observations to map the large scale kinematics of galaxies has been evidenced in recent studies (e.g. Ganda et al. 2003). For AGN, only few such studies are available (e.g. Emsellem et al. 2006 for NGC 1068). Most AGN kinematic studies have focused on gas emission lines, as it is much easier to obtain kinematical data from emission lines than from stellar absorption features. Nevertheless, the gas in the nuclear region of AGNs is subject to non-gravitational effects, such as winds and jets, and in order to probe the gravitational potential, it is necessary to measure the stellar kinematics.

In this work, we use the IFU-GMOS to map the stellar kinematics in the inner few hundred parsecs of 6 of the closest Seyfert galaxies. The combination of the spatial resolution at the galaxies reached by the observations (down to a few tens of parsecs), 2D coverage, stellar kinematics, and a Seyfert sample is unique in the literature.

This paper is organized as follows. In Section 2 we present the criteria used to select the sample and discuss the relevant information for each galaxy. In Section 3 we describe the observations and reductions, in section 4 we present the methods used to analyze the data and in Section 5 we report and discuss our results. In section 6 we present a summary of the results and our conclusions.

2 SAMPLE

We chose to map the stellar kinematics using the Ca II triplet absorption feature around 8500Å (hereafter Ca-T) due to the fact that this spectral region is not much affected by emission lines and the continuum of the active nucleus, and thus clearer measurements of the stellar kinematics can be made.

The sample galaxies were selected as the closest Seyfert galaxies for which previous spectra in the Ca-T region were available in the literature (Nelson & Whittle 1993), so that we could check, in advance, if the absorption features to be used in the stellar kinematic measurements were clearly present in the spectra. In this work, we present the results for six Seyfert galaxies, whose properties are listed in Table 1.

Besides selecting the galaxies on the basis of their proximity and detectability of the stellar Ca-T, we also looked for the presence of strong [S II] $\lambda$9069 line emission, as this line could be included in the same observational set up used to observe the Ca-T. The results based on the measurements of this emission-line, such as intensity maps and gaseous kinematics, will be presented in a forthcoming paper.

We have also observed kinematic standard stars, to be used as references in the measurement of the radial velocities and velocity dispersions of the sample galaxies.

2.1 NGC 2273

From a 6 cm radio map, Ulvestad & Wilson (1984) found the nucleus to be resolved into two distinct components separated by 0.9 along E-W. Ferruit, Wilson & Mulchaey (2000), using HST, resolved the central ovoid of the galaxy, which shows two arc-like structures forming a partial nuclear ring, with semi-major axis of $\sim 2.5$, observed both in a broad-band and in a [N II]+H$^\alpha$ emission-line image. They suggest that emission in the ring, also weakly observed in [O III], comes from H II regions.

The partial ring is also detected in a color map log (F547M/F791W) which presents lower values to NW suggesting this is the near side of the ring. The analysis of the [O III] and [N II]+H$^\alpha$ emission line images reveals a jet-like structure which extends by 2'' to E of the nucleus and is aligned with the radio structures observed in 6 cm.

Subsequent investigation (Erwin & Sparke 2003) based on HST images and colour maps led the authors to classify the nuclear ring as a star-forming ring. They also classified the structure internal to the ring as a luminous two-armed blue spiral in opposition to a previous bar-like interpretation (Mulchaey & Regan 1993). The large $H-K$ colour index and high 10$\mu$m luminosity, extended by more than 5'' also supports the presence of a circumnuclear starburst (Devereux 1981; Young & Devereux 1991).

2.2 NGC 3227

This galaxy forms an interacting pair with the elliptical galaxy NGC 3226. Gonzalez Delgado & Perez (1997) reported traces of young stellar population in the nuclear optical spectrum. Mundell et al. (1992) studied the H$^\alpha$ emission and found that the galaxy disk is inclined by 56°with
major axis at PA = 158° and contains an H I mass of $5.7 \times 10^8$ $M_\odot$. H$_2$ maps have been obtained by Quillen et al. (1997) from HST/NICMOS images and show elongated emission along PA $\sim 100°$. Meixner et al. (1999) obtained $^{12}$CO (1-0) maps showing a nuclear double peak aligned roughly E-W separated by 2′ and extended emission running from SE to NW at 30° from the major axis of the galaxy (the direction pointing to the companion galaxy NGC 3226). To explain these maps Fernandez et al. (1999) proposed a gas “disk” of 0.1 pc diameter with a major axis along PA $= 158°$.

NW component. The kinematical analysis led them to conclude that a warped gas disk provides a better description of the observed gas motions than a bar.

### 2.3 NGC 3516

This was the first Seyfert galaxy with detected line variability (Andrillat & Souffrin 1968). More recently Weaver Gelbord & Yaqoob (2001) observed variability in both the X-ray continuum and Ke line. Regan & Mulchaey (1999), using HST images showed that a single dust spiral pattern dominates the nuclear morphology. Using J-band images Quillen et al. (1997) proposed that this galaxy has two bars. Nagar et al. (1992) found a radio jet along P.A. $\sim 10°$ which corresponds to the near side of the galaxy, according to Malkan, Gorjian & Tani (1998), so this jet would be projected against the near side of the galaxy. Hα + [Nii] and [Oiii] images show a “Z”-shaped circumnuclear emission extended by $\sim 20''$ from SW to NE (Pogge 1989). Mivaij, Wilson & Perez-Fournon (1992). The gas velocities inside this structure cannot be reproduced by rotation, but can be explained by a nuclear outflow (Mulchaey et al. 1992, Veilleux, Tully, & Bland-Hawthorn 1993). The galactic disc does not contain H II regions, according to Gonzalez Delgado et al. (1999).

Arribas et al. (1997) presented 2D stellar kinematics over a similar field to ours but with poorer spatial resolution. Details about their data and a comparison to ours are discussed in Sec. 4.

### 2.4 NGC 4051

Using [Oiii] emission-line archival HST images, Schmitt & Kinney (1996) found an unresolved nuclear source and a low surface brightness component extending 10′ from the nucleus along PA = 100°, approximately the same orientation as that connecting the two radio components at 6 cm detected by Ulvestad & Wilson (1984), which are separated by 0′.4. In radio 6 and 20 cm but with a resolution of 5′ Ho & Ulvestad (2001) detected a larger scale component extending to SW and NE from the nucleus. Veilleux (1991) reported blue wings in the forbidden optical emission lines and proposed a model with outflow and obscuring dust. The mid and far infrared fluxes have been explained by Rodriguez Espinosa et al. (1996) and Contini & Viegas (1999) as due to hot dust emission. In X-rays Lawrence et al. (1985) found variability on time scales of hundreds of seconds and Salvati et al. (1993) reported a flux change by a factor 2 at 2.2 μm in 6 months. Using X-ray maps of the nuclear region Singh (1999) proposed the existence of a component associated with the nuclear activity and other associated with a starburst extended by $\sim 40''$.

### 2.5 NGC 4593

This is a Seyfert 1 galaxy with detected nuclear variability in X-rays by Weaver Gelbord & Yaqoob (2001) and in the optical and infrared by Winkler et al. (1992). Kotilainen, Ward & Williger (1993) and Kotilainen & Ward (1994). The Ho map obtained by Gonzalez Delgado et al. (1997) shows ionized gas in a nuclear halo with radius 2-3′′ elongated N to S, and at the border of the halo some patches of emission which they suggest to be a broken starburst ring with minor axis length $\sim 50$ running S to N. There are a number of H II regions in the spiral arms but none in the large scale bar (Evans et al. 1999).

### 2.6 NGC 4941

According to the hard and soft X-rays spectra, Maiolino, Risaliti & Salvati (1999) calculated that the nucleus of this galaxy has a column density of $N_H = 4.5 \times 10^{20}$ cm$^{-2}$. Extended [Oiii] emission (Pogge 1989) shows an halo shape extending up to $\sim 10''$ from the nucleus while Ho emission is concentrated in H II regions along the spiral arms. Schmitt et al. (2001) found two resolved radio components separated by 15 pc along PA = 335°.

### 3 OBSERVATIONS AND REDUCTIONS

The data were obtained in queue mode over three semesters at the Gemini North telescope, using the GMOS IFU. The instrumental setup for each program is shown in
Table 2 The spectral resolution was $R \sim 3000$ (FWHM $\sim 100$ km s$^{-1}$) with a wavelength sampling of 0.692 Å/pix. The GMOS IFU consists of an hexagonal array of 1000 lenslets which send the light through optical fibers to the spectrograph. The lenslet array samples a field-of-view (FOV) of $7'' \times 5''$. The sky is sampled with a field which is displaced by 1 arcmin from the object and has one half of the size of the object field. The centres of contiguous lenses are separated by 0.72, which is also the distance between opposite faces of the hexagonal lenses. The effective slit aperture for every lens is, however, 0.631.

Each half of the fibres (corresponding to half of the FOV) is aligned to a separate pseudo-slit. The data can be obtained using both slits (full FOV) or one slit (half the FOV, or $3.5'' \times 5''$) with twice the wavelength coverage. The spectra are projected into an array of three $2048 \times 4608$ EEV chips disposed side by side with small gaps in between. The peaks of contiguous spectra are separated by ~ 5 pixels. In two-slit mode each pseudo-slit illuminates one side of the array, and the use of passband filters avoids spectral overlap.

Before the spectral observations, one direct image was obtained for centering purposes, allowing an evaluation of the image quality. This value, measured as the FWHM of the stellar PSFs in the field, is listed in Table 1.

Data reduction was accomplished using generic IRAF1 tasks as well as specific tasks developed for GMOS data in the gemini.gmos package. The reduction process comprised trimming, bias subtraction, flat-fielding, cosmic rays cleaning, alignment and interpolation of the data across the chips to recover all the spectra in one frame, extraction of the spectra (the tracing is done using flat spectra), wavelength calibration, sky subtraction and co-addition of different exposures.

In Fig. 1 we show, for each galaxy, the spectra from selected lenses. The left panels show the nuclear spectra, defined as the one with the strongest flux in the continuum around 8500 Å. The right panel shows the spectra corresponding to a lens located at 1.7 from the centre of the array, towards the left side of the IFU field.

The nuclear spectra of the Seyfert 1 galaxies NGC 4051 and NGC 4593 present too much contamination from the AGN continuum and emission lines. In the case of NGC 4051 these lines include the OI blend at $\lambda$446, Ca-T in emission and a number of Paschen emission lines. In the case of NGC 4593 the OI emission is very broad and there are a number of other emission lines (e.g. NII $\lambda$703.2). These strong emission lines precluded the measurements of the stellar kinematics within ~ 0.58 from the nucleus in these galaxies. This effect was unexpected on the basis of the previously inspected integrated spectra (Nelson & Whittle 1993), probably because it was diluted in their large aperture. In any case, the information we could obtain for these galaxies outside the contaminated region is still valuable and have been included in the present work. The spectra of the Seyfert 1.5 galaxies NGC 3227 and NGC 3516 (some authors classify the latter as Sy 1) present weak contamination from the broad OI line which, however, does not affect the measurements significantly, as the two strongest absorption lines of the Ca-T are unaffected.

4 DATA ANALYSIS

4.1 Velocity measurements; cross-correlation technique

The kinematic measurements were performed by cross-correlating the spectra of individual lenslets with the spectrum of a kinematic standard star observed with the same setup as the galaxies. The cross-correlation was performed using the task xcsao of the package xvsaor (Kurtz & Mink 1993) in IRAF, over the spectral range 8430-8900 Å which includes the Ca-T features but avoids the noisy regions at the extremes of the spectra. The task uses the method of the quotient of the Fourier transforms applied to the spectra in velocity space and searches for the peak of the cross-correlation function, fitting a quartic function to the data with values above 50% of the peak and giving as outputs the peak velocity and the full width at half maximum (FWHM) of the cross-correlation function.

As the surface brightness of the galaxies decreases towards the borders of the field, in order to improve the signal-to-noise ratio at these locations, we replaced each individual spectrum by the average of itself and the 6 nearest spectra (which are closer than 0.73). This replacement was done for the spectra beyond a radius 1'' from the centroid of the 8500 Å continuum brightness distribution.

In order to obtain the velocity dispersion values from the measured line widths we have convolved the spectrum of the kinematic standard star with Gaussian curves of known FWHM – where FWHM = $2.35 \sigma$, and $\sigma$ is the velocity dispersion – to create a set of synthetic spectra. We then performed the cross correlation between these synthetic spectra and that of the kinematic standard, measuring the FWHM of the cross correlation function as we did for the galaxies. By plotting the measured widths against the known Gaussian widths we obtained a very tight linear relation which is then used to obtain the real FWHM from the measured FWHM for each galaxy. Finally, as the radial velocities are measured relative to the kinematic standard star, the radial velocity obtained for each galaxy was corrected by the observatory motion relative to the local standard of rest and by the standard star radial velocity as determined from the shifts between the measured wavelengths of the Ca-T lines in the standard spectrum and their rest wavelengths.

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1 IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.
Figure 1. Typical spectra of our sample. In the left panels we show the nuclear spectra of the lens with the strongest continuum flux (adopted as corresponding to the nucleus) and in the right panels the spectra of a lens displaced 1'' left from the centre of the array. Each left-right spectra pair corresponds to the same galaxy and is identified by a label in the left panel. The spectra have been brought to rest frame and the main spectral features are identified by vertical dashed lines.
Table 2. Details of the observations.

| PROGID         | Date (MM/YYYY) | Observed galaxies | Field size (′) | Exp Time (s) | Grating/Filter | Spec. coverage (Å) |
|----------------|----------------|-------------------|----------------|--------------|----------------|--------------------|
| GN-2002B-Q-15  | 12/2002        | NGC 3227, NGC 3516 | 3.5×5          | 1440         | R400/RG610/G0307 | 6400 - 10400       |
|                |                | BD +31 22 14       |                | 1440         | R400/RG610/G0307 |                    |
| GN-2003A-Q-20  | 03/2003        | NGC 4051, NGC 4941 | 7×5            | 1800         | R400/CaT/G0309  | 8250 - 9450        |
|                |                | BD +21 24 25       |                | 1800         | R400/CaT/G0309  |                    |
| GN-2004A-Q-1   | 02/2004        | NGC 2273, NGC 4593 | 7×5            | 3600         | R400/CaT/G0309  | 7700 - 9500        |
|                |                | BD +31 22 14       |                | 3600         | R400/CaT/G0309  |                    |

4.2 Error calculation

The IRAF cross-correlation task `xcsao` calculates the error following the method of Tonry & Davis (1979), which is similar to that used by Nelson & Whittle (1995). This method uses the signal-to-noise ratio \( R \) and the FWHM \( \sigma \) of the cross-correlation peak, assuming that the error in \( \sigma \) is the same as in \( V \):

\[
\text{error} = \Delta \sigma = \Delta V_r \approx \frac{3w}{8(1 + R)}
\]

(1)

For the spectra where the Ca-T lines are clearly detected and are not contaminated by emission lines, we obtain errors in the range 4-17 km s\(^{-1}\) for all galaxies. However, there is a loose correlation between the velocity dispersion measurements and the error calculated by this formula, due to a dependence in \( w \) that is not fully canceled by \((1 + R)\), an effect also pointed out by Nelson & Whittle (1995). This led us to adopt a conservative approach regarding the error reported by the `xcsao` task. After inspecting some representative spectra and the calculated error values, we adopted 15 km s\(^{-1}\) as the errors in our individual measurements for \( V_r \) and \( \sigma \). We note that this is actually an upper limit, which may overestimate the actual errors for some of the measurements, in particular the ones from the more central spectra.

4.3 Alternative velocity measurements; pixel fitting technique

In order to investigate the dependence of the velocity fields and in particular of the velocity dispersions \( \sigma \) on the measurement technique we have carried out a kinematic analysis in pixel space (Barth et al. 2002; Cappellari & Emsellem 2004).

Our implementation of the direct-fitting-method is essentially the one used in Garcia-Rissmann et al. (2003), the only difference being that we rectified all spectra to account for the different slopes of stellar and galaxy spectra.

We have compared our cross-correlation results with results obtained with this method. We find that the radial velocity measurements are essentially unaltered. We also find that the patterns in the velocity dispersion maps remain the same. We do find a systematic difference in the velocity dispersion values obtained from the two methods but this difference varies from galaxy to galaxy. For example, for NGC 4051 there is no difference at all while for NGC 2273 we find the largest difference. This is illustrated in Fig. 2, where we compare the \( \sigma \) maps obtained with both techniques for NGC 2273. Note that the low dispersion ring (see discussion in Section 5.1) is clearly present in both maps, the only difference being that the values obtained with the direct pixel fitting method are larger by \( \approx 20 - 30 \) km s\(^{-1}\).

In order to investigate if this difference could be due to a template mismatch, we have performed velocity dispersion measurements using both techniques and a set of 28 stellar templates from the atlas of Cenarro et al. (2001). The stars were chosen to span a wide range of spectral types. For the cross-correlation technique the results did not vary much for template spectral types G, K and M. Nevertheless, as we moved to earlier spectral types the results began to vary but by simple visual inspection of these template spectra we verified that they are bad matches to the galaxy spectra. In the case of the direct pixel fitting method we made two tests. First we modeled each spectrum with a combination of all 28 templates, letting their proportions vary freely, thus accounting for variations in stellar populations (García-Rissmann et al. 2003). Then we repeated the fit using only our observed template star. The difference is negligible (at most a few km s\(^{-1}\)), demonstrating that our kinematic measurements are not seriously affected by template mismatch.

4.4 Modeling of the radial velocity field

The radial velocity maps obtained from the measurements described above (see Fig. 3) show that a clear rotation pattern dominates the stellar kinematics. In order to obtain an analytical description of the radial velocity field, we have adopted a very simple approximation, assuming plane keplerian orbits for the stars, and representing the gravitational potential of the bulge by a Plummer potential:

\[
\Phi = -\frac{GM}{\sqrt{r^2 + a^2}}
\]

(2)

which depends only on the scale length \( a \) and bulge mass \( M \), and where \( r \) is the radial distance in the plane of the galaxy.

We assume that the stars are in orbits close to a plane \( P(t, \psi_0) \) characterized by its inclination relative to the plane of the sky \( i \) and the position angle (PA) of the line of nodes \( \psi_0 \). Although we do not expect that this simple approximation provides a robust determination of the bulge mass,
inclination and bulge scale length, we can obtain reliable determination of the systemic velocity \( V_r \), PA of the line of nodes \( \psi_0 \) and the position of the kinematical centre.

Using the above potential, we calculate the rotation curve in the plane \( P(i, \psi_0) \) with coordinates of the origin \((X_0, Y_0)\). The 2D rotation curve is then projected onto the plane of the sky where the radial variable is now \( R \), the angular variable is \( \psi \) and the correspondent scale length is \( A \). The relations between \( r \) and \( R \), and between \( a \) and \( A \) are: \( r = \alpha R \) and \( a = \alpha A \), where \( \alpha = \sqrt{\cos^2(\psi - \psi_0) + \frac{\sin^2(\psi - \psi_0)}{\cos^2(\psi)}} \). The systemic velocity \( V_r \) is added to the model as a zero point offset.

In summary, there are 7 free parameters to be determined by fitting the non-linear model

\[
V_r = \frac{R^2 GM}{(R^2 + A^2)^{3/2}} \sin(i) \cos(\psi - \psi_0) \left( \cos^2(\psi - \psi_0) + \frac{\sin^2(\psi - \psi_0)}{\cos^2(\psi)} \right)^{3/4}
\]

(3)

to the data \( V_r \), what has been done using a Levenberg-Marquardt algorithm.

Before performing the fits, we have inspected the map of uncertainties in radial velocity generated by the cross-correlation routine, the individual spectra and the radial velocity maps in order to obtain an uncertainty threshold to discriminate between reliable data (or measurement) and noise. This threshold varied somewhat from galaxy to galaxy, ranging from 9 to 17 km s\(^{-1}\). Only reliable measurements were used in the data analysis and model fitting. The measurements considered unreliable have been masked in the velocity maps shown in Figs. 3S.

The parameters obtained from the fits are shown in Table 4S. The kinematical centre \((X_0, Y_0)\) was used to calculate \( \Delta X_0 = X_0 - X_0^b \) and \( \Delta Y_0 = Y_0 - Y_0^b \) where \( X_0^b \) and \( Y_0^b \) are the coordinates of the centroid of the continuum brightness distribution.

5 RESULTS

In this section we present and discuss the kinematic measurements obtained from the spectra as well as the results of the modeling.

2D maps of the measurements, together with the acquisition image and residuals of the model fits for each galaxy, are presented in Figs. 3S-8S. Each figure comprises 6 panels, as described below.

(i) The top left panel shows a large scale \( I \)-band image with the IFU field drawn as a white box and the peak of the brightness distribution marked by the black cross. The small inset at the lower right corner represents the maximum uncertainty of the nuclear region covered by the IFU field.

(ii) The top right panel shows the measured radial velocities \( V_r \) (red crosses) along a virtual slit placed along the line of nodes and with width 0\textquotesingle 6, together with the corresponding model values (blue circles), as a function of the projected distance from the nucleus\(^2 \) \( R \). The error bar at the lower right corner represents the maximum uncertainty in the velocity values.

(iii) The remaining panels show 2D maps of measured properties. The middle left panel shows the flux integrated over the wavelength range used in the cross-correlation measurements.

(iv) The middle right panel shows the radial velocity map.

\(^2\) Note that, due to the fact that the slit width includes more than one lens there may be more than one velocity value for each given radius at the slit, even for the model.
with isovelocity contours superimposed; white contours correspond to the measurements, while grey contours correspond to the best fit model. The kinematic centre is identified by the black cross, and the line of nodes is indicated by the black dashed line.

(v) The bottom left panel shows the velocity dispersion map.

(vi) The bottom right panel shows the residuals obtained from the subtraction of the kinematic model from the radial velocity map of panel (iii).

For display purposes, the kinematic maps of Figs. 3-8 have been interpolated over the original hexagonal array to generate a rectangular grid uniformly sampled, with pixel size 0\('
' \times \text{6}'. The scale (shown in panel (iii)) and orientation (shown in panel (v)) are the same for all the maps for a given galaxy.

Table 3 lists the velocity dispersions measured from the integrated nuclear spectra inside circular\(^3\) apertures with diameters 0\,'
' \times 0\,'
' for those galaxies with reliable nuclear data, as discussed in Section 3. Comparing our values with those from Nelson & Whittle (1993), we conclude that they are compatible given the uncertainties and our smaller apertures. The value given by Terlevich et al. (1990) for NGC 3516 is significantly larger than ours, but these authors also present higher values than those of Nelson & Whittle (1993) for other galaxies in common. For NGC 4051 and NGC 4593 the central velocity dispersions are unreliable due to the strong contribution from the AGN continuum.

We now discuss the results obtained for each galaxy.

### 5.1 NGC 2273

The radial velocity map (central right panel of Fig. 3) shows a rotation pattern which deviates from the classical spider diagram, evidenced by the fact that the observed kinematic minor and major axes are not perpendicular to each other, indicating deviations from axial symmetry. The residuals map show indeed deviations from the model above the noise level, which seem to be co-spatial with the star-forming ring (see discussion below).

The rotation curve (upper right panel of Fig. 4) along

\[^3\] Actually the combined spectra from all hexagonal elements with centres within the circular aperture radii.

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**Table 3. Parameters derived from our modeling.**

| Galaxy   | \(V_s\) (km/s)\(^a\) | \(\Psi_0\) (\(^\circ\)) | \(\Delta X_0\) (pc) | \(\Delta Y_0\) (pc) | \(M\) \((\times 10^5 M_\odot)\) | \(A\) (kpc) | \(i\) (\(^\circ\)) |
|----------|----------------------|-------------------------|--------------------|--------------------|-------------------------------|-------------|-------------|
| NGC 2273 | 1836                 | 233.4                   | -7 ± 12            | -20 ± 12           | 2.4                           | 0.17        | 51          |
| NGC 3227 | 1201                 | 149.7                   | -2 ± 9             | -10 ± 9            | 1.4                           | 0.11        | 43          |
| NGC 3516 | 2698                 | 48.4                    | -18 ± 18           | 9 ± 18             | 15                            | 0.28        | 22          |
| NGC 4051 | 718                  | 106.5                   | 4 ± 5              | 8 ± 5              | 0.084                         | 0.031       | 31          |
| NGC 4593 | 2531                 | 88.5                    | 1 ± 17             | 4 ± 17             | 18                            | 0.41        | 25          |
| NGC 4941 | 1161                 | -0.2                    | 1 ± 7              | -14 ± 7            | 3.6                           | 0.24        | 24          |

\(^a\) The upper limit for the error in \(V_s\) is about 15 km s\(^{-1}\).

\(^b\) \(\Delta X_0\) and \(\Delta Y_0\) are measured relative to the continuum centroid (see text).

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**Table 4. Comparison between our \(\sigma\) measurements and those from the literature for the central spectra.**

| Galaxy    | \(\sigma\) (0\,'
' \times 0\,'
' ) (km/s) | \(\sigma\) (1\,'
' \times 1\,'
' ) (km/s) | \(\sigma\) (NW95) (km/s) | Aperture (\(\times\)) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| NGC 2273  | 104             | 105             | 136 ± 22        | 1.5 \(\times\) 1.4 |
| NGC 3227  | 114             | 109             | 128 ± 13        | 1.5 \(\times\) 2.1 |
| NGC 3516  | 192             | 178             | 235\(^a\)       | 2.1             |
| NGC 4051  | 85\(^b\)        | -               | 88 ± 13         | 1.5 \(\times\) 2.1 |
| NGC 4593  | 105\(^b\)       | -               | 124 ± 28        | 1.5 \(\times\) 3.5 |
| NGC 4941  | 138             | 136             | 109 ± 13        | 1.5 \(\times\) 2.1 |

\(^a\) From Terlevich et al. (1990).

\(^b\) These values were obtained by inspection of the region around the contaminated central portion of the maps. See Sec. 4 for details.

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the kinematic major axis seems to have reached the turnover at only 250 pc from the nucleus. In addition, the data turnover seems to be more pronounced than that of the model, suggesting a more concentrated mass distribution.

The velocity dispersion map (bottom left panel of Fig. 3) presents a ring-like structure with values of about 60-80 km s\(^{-1}\) while in the centre the velocity dispersion reaches values of up to 100 km s\(^{-1}\). In Fig. 4 we present one-dimensional cuts of the velocity dispersion map along the major and minor axis of the galaxy which helps the visualization of the ring-like structure. This structure is co-spatial with the nuclear partial ring observed in the HST line emission images and color maps of Ferruit, Wilson & Mulchaey (2000). The lower velocity dispersion can be interpreted as a signature of recently formed stars, which still keep – at least partially – the kinematics of the gas from which they have been formed (Wozniak et al. 2003) and thus map the location of a starburst ring with semi-major axis of \(\sim\) 300 pc.

### 5.2 NGC 3227

Our radial velocity map (central right panel of Fig. 4) also shows a rotation pattern, where the redshifted side is to SE of the nucleus, in agreement with the H\(\text{I}\) radial velocity data of Schinnerer, Eckart & Tacconi (2000). The line
Figure 3. Kinematic data for NGC 2273. The upper left panel shows a large scale $i'$-band image of the galaxy (spatial units are arcsec) with the IFU field overlaid as a white box and an inset detailing the nuclear region within the FOV of the IFU maps. The central left panel shows the flux integrated over the wavelength range of the cross-correlation measurements. The bottom left panel shows the velocity dispersion map. The upper right panel shows the measured radial velocities from a virtual slit placed along the line of nodes (red), together with the corresponding model values in (blue). The central right panel shows the radial velocity map with isovelocity contours from data and model superimposed (white for the measurements and grey for the model); the cross marks the kinematic centre and the dashed line shows the line of nodes. The bottom left panel shows the velocity dispersion map. The bottom right panel shows the residuals between the measured radial velocities and the model. All panels have the same orientation, indicated at the bottom right panel. The four bottom panels share the scale indicated in the central right panel, and angular extents of $6''8 \times 4''9$. Regions in white correspond to uncertain measurements which have not been included in the fits.
Figure 4. Kinematic data for NGC 3227. Details are as described in the caption of Fig. 3, except for the fact that the IFU field is half the size, or 3'9 x 4'9.
Figure 5. Kinematic data for NGC 3516. Details are as described in the caption of Fig. 3 except for the fact that the IFU field is half the size, or 3\arcsec.9 × 4\arcsec.9.
Figure 6. Kinematic data for NGC 4051. Details are as described in the caption of Fig. 3.
Figure 7. Kinematic data for NGC 4593. Details are as described in the caption of Fig. 6.

IFU stellar kinematics of active galaxies
Figure 8. Kinematic data for NGC 4941. Details are as described in the caption of Fig. 3.
of nodes PA obtained from the model (= 156.7°) agrees within 4° with the values found by Mundell et al. (1992) and Schinnerer, Eckart & Tacconi (2001).

The residuals from the model fitting, shown in the bottom right panel of Fig. 4, are mostly below ±15 km s\(^{-1}\), except for two blueshifted regions approximately along the line of nodes, which deviate from the model by more than 20 km s\(^{-1}\). The rotation curve (upper right panel) suggests that to NW the turnover has been reached already at ~150 pc from the nucleus, while this does not happen to the SE.

The velocity dispersion map (bottom left panel of Fig. 5) is characterized by a nuclear region with σ above 100 km s\(^{-1}\) which drops in all directions but towards SE reaching values of ~75 km s\(^{-1}\) or less. The values increase again towards E, N and NW as evidenced in Fig. 10 by two one-dimensional cuts of the σ map. The loci of low σ regions have a good correspondence to the loci of high CO emission reported by Schinnerer, Eckart & Tacconi (2001) and referred to as a gas ring. In particular, the loci with the lowest velocity dispersions correspond to those with highest CO emission. The loci of low σ coincides with a ring of recent star formation where the low σ rings support the existence of a low σ ring structure in our data. As in the case of NGC 2273 our interpretation is that we are observing a ring of recent star formation where the low σ of the stars is due to the low velocity dispersion of the cool gas from which they have formed.

5.3 NGC 3516

The radial velocity map (central right panel of Fig. 5) shows a rotation pattern which seems to reach the turnover at the edge of the field, corresponding to a distance of 500 pc from the nucleus, as can be also seen in the rotation curve (top right panel of Fig. 5). The velocity field is in good agreement with the 2D velocity map of Arribas et al. (1997). The kinematic major axis orientation of Ψ\(_0\) = 48.4° also agrees with the values found by these authors. The above value for Ψ\(_0\) is also the orientation of the photometric major axis obtained by fitting ellipses to the most external isophotes in the i-band acquisition image (corresponding to an ellipse of semi-major axis 49″).

From the rotation curve in the top right panel of Fig. 5 we obtain a peak-to-peak amplitude in the velocity field of ~220 km s\(^{-1}\), significantly larger than the one measured by Arribas et al. (1997) (160 km s\(^{-1}\)). This discrepancy can be understood if we recall that those authors applied a 1″5 smoothing to the data, which would flatten the rotation curve. We note that the peak-to-peak amplitude of the stellar rotation is well below the one obtained from the gas kinematics (592 km s\(^{-1}\)), by Mulchaey et al. (1992).

Our velocity dispersion map (bottom left panel of Fig. 5) shows typical values in the central region larger than 150 km s\(^{-1}\) surrounded by a region with lower σ (as low as ~90 km s\(^{-1}\)). From measurements of the Mg\(_{\text{II}}\) absorption band, Arribas et al. (1997) reported a central σ of 164 ± 35 km s\(^{-1}\) (within an aperture of 3″), which is consistent with our data, but a 2D distribution of line widths does not show any clear structure. In our data we can see lower σ values at locations surrounding the kinematic major axis direction at an average distance from the nucleus of ~400 pc.

The residuals from the radial velocity fit (bottom right panel of Fig. 5) are mostly within the adopted error of ±15 km s\(^{-1}\).

5.4 NGC 4051

In this galaxy the nuclear continuum and broad Ca-T emission lines preclude reliable measurements of the stellar kinematics using the Ca-T absorption lines within 0″5 from the nucleus. This region has thus been masked for the model fitting.

The radial velocity map (central right panel of Fig. 5)
is dominated by the typical rotation pattern observed in all galaxies so far. The rotation curve (upper right panel of Fig. 8) has a peak-to-peak amplitude of only 130 km s\(^{-1}\) for an inclination of the galaxy \(i \sim 41^\circ\) (assuming \(i = \cos^{-1} b/a\) where \(a\) and \(b\) are the major and minor axis photometric lengths obtained from NED) and the turnover seems to occur very close to the nucleus, at \(R \sim 50\) pc.

The residuals from the model fit are within the \(\pm 10\) km s\(^{-1}\) error limits (bottom right panel of Fig. 8) and do not show any well defined structure.

The velocity dispersion map (bottom left panel of Fig. 8), is also irregular with \(\sigma\) values ranging from a minimum of \(\sim 60\) km s\(^{-1}\) to a maximum of \(\sim 100\) km s\(^{-1}\). Nevertheless it was not possible to extend the measurements closer to the nucleus than \(\sim 0.5^\prime\), making it difficult to draw any conclusion on the \(\sigma\) distribution.

### 5.5 NGC 4593

For this galaxy, as for NGC 4051, the continuum from the Seyfert nucleus precludes reliable measurements of the stellar kinematics in the central region.

The radial velocity map (central right panel of Fig. 8) shows a clear rotation pattern in which the kinematical major axis runs approximately along E-W with the redshifted side to the E.

The peak-to-peak amplitude of the velocity field is 255 km s\(^{-1}\), but the rotation curve (top right panel of Fig. 8) suggests that the maximum velocity may occur beyond the edges of the observed FOV, which corresponds to \(\sim 700\) pc from the nucleus along the kinematic major axis.

The velocity dispersion map (bottom left panel of Fig. 8) hints on the presence of a partial ring structure also for this galaxy. This is supported by the one-dimensional cuts along the major and minor axis of the velocity dispersion map shown in Fig. 11. Alternatively this region of low \(\sigma\) values can be associated with a tightly wound spiral arm which can be observed in an HST F547M image from Malkan, Gorjian & Tam (1998).

Figure 11. One dimensional cuts of the 2D \(\sigma\) map of NGC 4593 within pseudo slits 0.3 wide crossing the nucleus at PA = 260\(^\circ\) and PA = 20\(^\circ\).

A rotation pattern is again observed in the stellar kinematics (central right panel of Fig. 8). The rotation curve (top right panel of Fig. 8) indicates that the maximum amplitude is located beyond the observed region, which corresponds to a radial distance from the nucleus of only 200 pc for this galaxy.

The velocity dispersion map (bottom left panel of Fig. 8) is almost flat within \(\sim 100\) pc from the nucleus, with central values \(\sim 135\) km s\(^{-1}\), decreasing to \(\sim 100\) km s\(^{-1}\) at the edges of the field (\(\sim 200\) pc).

The radial velocity residuals (bottom right panel of Fig. 8) are within the \(\pm 15\) km s\(^{-1}\) error limit and show no obvious pattern.

### 6 SUMMARY AND CONCLUSIONS

In this work we have obtained 2D maps of the stellar kinematics of the inner few hundred parsecs of 6 nearby Seyfert galaxies at sub-arcsecond angular resolution, corresponding to spatial resolutions ranging from 30 to 180 parsecs at the galaxies.

The stellar velocity field is dominated by rotation, well represented by a simple model where the stars follow plane circular orbits under a Plummer potential. The residuals between measured and modeled radial velocities are always smaller than \(\pm 25\) km s\(^{-1}\).

In most cases, the turnover of the rotation curve seems to occur within or close to the edges of the observed field, at radial distances ranging from \(\sim 50\) pc for NGC 4051 to \(\sim 500 - 700\) pc for NGC 3516 and NGC 4593. Only for NGC 4941, for which our observations reach only as far as \(\sim 200\) pc from the nucleus, the turnover was not observed within the IFU FOV.

The case of NGC 4051 is particularly interesting because the turnover is at only \(\sim 50\) pc from the nucleus, suggesting that the stellar motions are dominated by a highly concentrated gravitational potential. Indeed, the scale length of the Plummer potential obtained for this galaxy is the smallest of the the sample, \(A = 31\) pc.

5.6 NGC 4941
Adopting $\sigma = 85 \text{km s}^{-1}$ for the nuclear velocity dispersion (the mean value of innermost usable pixels), and the $M_\text{BH} - \sigma$ relation, we infer a black hole mass of $4.5 \times 10^9 M_\odot$, which implies a sphere of influence of only 2.5 pc radius. These values are consistent with those by Peterson et al. (2004), who obtained a black hole mass of $1.9 \times 10^9 M_\odot$ corresponding to a sphere of influence of 1.2 pc radius. Such concentrated potential is unlikely to be responsible for the small potential-scale size we have found. A more likely interpretation is that the bulge is itself compact and concentrated. Indeed, unlike most Seyferts, this galaxy is late type (Scd), with a small bulge effective radius.

The velocity dispersion maps are featureless for NGC 4051 and NGC 4941. For the other galaxies the velocity dispersion maps show higher values at the centre and smaller values at 200 – 400 pc from the nucleus. In the case of NGC 3516 the lowest $\sigma$ values are observed towards the border of the IFU field, at location close to the kinematic major axis. For NGC 2273, the spatial distribution of lower $\sigma$ values defines a ring-like morphology which is co-spatial with partial nuclear ring structures seen in line emission images and color maps of previous works. For NGC 3227, the velocity dispersion map shows a very good correspondence between the region of low $\sigma$ values – which seems to delineates a partial ring structure – and regions of high [12CO (2-1)] emission and blue $J - K$ colours observed in previous works. A partial ring of low $\sigma$ values is also hinted in NGC 4593. As for the nuclear $\sigma$-drops found by previous authors (e.g. Emsellem et al. 2001; García-Lorenzo et al. 1999; Marquez et al. 2003) the circumnuclear $\sigma$-drops we found in the present study can be interpreted as regions of higher (past or present) gas concentration, harboring younger stars which still preserve the lower velocity dispersion of the original gas from which they have formed.

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