Near-infrared imaging and spectroscopy of the nuclear region of the disturbed Virgo cluster spiral NGC 4438*

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ABSTRACT
We present near-infrared (NIR) Very Large Telescope (VLT) Infrared Spectrometer and Array Camera (ISAAC) imaging and spectroscopy of the peculiar Virgo galaxy NGC 4438, whose nucleus has been classified as a low-ionization nuclear emission-line region (LINER). The data are supplemented by mid-infrared imaging, and compared to previous HST broad-band images. Images and position-velocity maps of the [Fe ii] and H2 line emissions are presented and compared with the distribution of the optical narrow-line region and radio features. Our results show that shocks (possibly driven by a radio jet) contribute to an important fraction of the excitation of [Fe ii], while X-ray heating from a central active galactic nucleus (AGN) may be responsible for the H2 excitation. We address the question whether the outflow has an AGN or a starburst origin by providing new estimates of the central star formation rate and the kinetic energy associated with the gas. By fitting a Sérsic bulge, an exponential disc and a compact nuclear source to the light distribution, we decomposed NGC 4438’s light distribution and found an unresolved nuclear source at 0.8 arcsec resolution with $M_K = -18.7$ and $J - H = 0.69$. Our measured bulge velocity dispersion, 142 km s$^{-1}$, together with the standard $\sigma$–$M_{bh}$ relation, suggests a central black hole mass of $\log(M_{bh}/M_\odot) \sim 7.0$. The stellar kinematics measured from the NIR CO lines show a strong peak in the velocity dispersion of $\sigma_0 \sim 178$ km s$^{-1}$ in the central 0.5 arcsec, which is possible kinematic evidence of a central black hole. We calculated a general expression for the integrated Sérsic profile flux density in elliptical geometry, including the case of ‘discy’ isophotes.

Key words: galaxies: active – galaxies: individual: NGC 4438 – galaxies: starburst.

1 INTRODUCTION
NGC 4438 is a large peculiar spiral galaxy, with a disturbed stellar disc and an even more heavily disturbed interstellar medium (ISM). Located near the centre of the Virgo cluster, NGC 4438 has undergone a violent collision with the nearby giant elliptical M86 (Kenney et al. 2008), and may also be experiencing ongoing ram pressure stripping due to an interaction with the Virgo intracluster medium (Vollmer et al. 2009). NGC 4438’s nucleus has been classified as a particularly interesting low-ionization nuclear emission-line region (LINER; Heckman 1980). The spectra of LINERs are characterized by the presence of emission lines from atomic species of low-ionization state. By definition, LINERs are galaxies which host nuclei with emission-line ratios that satisfy the following criteria: $[O\text{ III}] \lambda 5007/\text{H}\beta < 3, [\text{O}\text{ I}] \lambda 6300/\text{H}\alpha > 0.05$ and $[\text{N}\text{ II}] \lambda 6583/\text{H}\alpha > 0.5$ (Osterbrock & Ferland 2005). Their emission line spectra are similar to those observed in narrow-line regions (NLRs) of gas in Seyfert 2 galaxies. However, some LINERs have relatively powerful central black holes, and tend to have broader emission lines (e.g. NGC 1052; Ho, Filippenko & Sargent 1997).

The most likely mechanism to explain the excitation in these objects is photoionization either from an active galactic nucleus (AGN) or from a strong stellar continuum (Ho, Filippenko & Sargent 2003). AGN photoionization models fit both the low-ionization spectra of LINERs and the high-ionization spectra of the Seyfert NLRs with similar nuclear emission, but different nebular conditions (such as the electron density and the incident ionising luminosity; see discussion by Ho et al. 2003; Osterbrock & Ferland 2005).

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The nucleus of NGC 4438 lies at the root of a nuclear bubble, expanding to the north-west (NW), which has been imaged in Hα+[N II] emission by Kenney & Yale (2002). In contrast with other similar systems, it is not clear what is powering this bubble, since there is neither a strong starburst nor a strong AGN in NGC 4438. For example, the galaxy NGC 2782 possesses a central starburst (extending over a radius ∼200 pc) which provides the mechanical luminosity that drives its central winds (Jogee, Kenney & Smith 1999). The Seyfert galaxy NGC 3079 harbours both a powerful AGN and a circumnuclear starburst (Veilleux et al. 1994), while M82’s outflows are driven only by a nuclear starburst (Lehner et al. 1999). Moreover, there are many other objects powered by composite systems where a circumnuclear starburst coexists with a central low-luminosity AGN (Rodríguez-Ardila, Riffel & Pastoriza 2005). Levenson et al. (2003) observed the Seyfert 2 starburst galaxy NGC 5135, distinguishing both the AGN (unresolved) and the starburst (spatially extended over ∼200 pc).

Broad Hα emission in NGC 4438 has been tentatively inferred by Ho et al. (1997) from the fitting of optical spectra. We have repeated the fitting of the Hα emission line profile on their data but with a smaller number of Gaussian components than Ho et al. (1997), obtaining similar results. Fig. 1 shows that a broad, full width at half-maximum (FWHM) ∼ 2050 km s⁻¹, Gaussian component is clearly present in the emission-line complex. This spectral feature is thought to be indicative of the presence of active nuclei harbouring a broad emission-line region (Ho et al. 1997).

Near-infrared (NIR) light can escape high opacity and dusty environments more easily than Hα photons can, making it possible to detect heavily obscured line-emitting regions. NIR emission lines, such as [Fe II] 1.257 μm and H2 2.122 μm, are less sensitive to extinction than optical lines such as Hα. NIR observations can provide better extinction estimates, and can yield new information on the intensity of a potentially obscured central AGN or starburst.

Results of a NIR spectroscopic survey of LINER galaxies carried out by Larkin et al. (1998), showed that the [Fe II] line (aD/τ₂ - aD/τ₁/2 at 1.257 μm) is the most commonly detected emission-line in LINERs (see also Rodríguez-Ardila et al. 2005). The H₂ line [1 - 0S(1) at 2.122 μm] is also a common feature. On the other hand, the Paβ emission line (or H I 3–5 at 1.282 μm), which is the strongest NIR recombination line available at low redshift in AGN and starburst galaxies, is only found in emission in 20 per cent of the LINER galaxies in Larkin et al. (1998) sample. Brγ (or H I 4–7 at 2.166 μm) is undetected in all the galaxies of the survey.

NGC 4438’s combination of peculiar spectral features, complex morphology and the possibility of studying the nuclear bubble at different wavelengths led us to obtain new NIR imaging and spectroscopic data. In this work, we present the results of Infrared Spectrometer and Array Camera (ISAAC) imaging and spectroscopy of NGC 4438, focusing on analysis of line emission maps and on two-dimensional modelling of the galaxy surface brightness. We want to study the morphology of NGC 4438 and whether there is a nuclear point source embedded in the bulge. In Section 2, we begin by giving a brief description of the observations. In Section 3, we discuss the nuclear line emission based on both imaging and spectroscopy, together with extinction estimates. In Section 3.3, we derived the line-of-sight stellar velocity dispersion from CO bands absorption features. In Section 4, we present the two-dimensional decomposition of the surface brightness of NGC 4438. In Section 5, we discuss and compare our findings with previous studies in the X-ray, optical and radio wavelengths, focusing on the energetics of the nuclear source and the surface brightness modelling results. Appendix A gives a detailed description of the data reduction of the imaging data. In Appendix B, we describe the surface brightness model used to fit the light distribution and how we measure structural parameters.

Throughout this paper, we use a distance to NGC 4438, near the centre of the Virgo cluster, of 16 Mpc (at which 1 arcsec corresponds to a distance scale of 77.6 pc). All the data reduction and analysis were carried out using the Perl Data Language (http://pdl.perl.org; Glazebrook et al. 1997). The stellar kinematics was derived using Interactive Data Language (http://www.itvis.com/idl/).

2 OBSERVATIONS

2.1 Imaging

We observed NGC 4438 with the Very Large Telescope (VLT) ISAAC imager and spectrograph (Moorwood et al. 1998), which has a field of view of 152 × 152 arcsec² and a pixel scale 0.148 arcsec pixel⁻¹. Our data consist of the following broad and narrow-band (NB) filters: J, H, Ks, NB1.26 μm, NB1.28 μm, NB2.07 μm and NB2.13 μm filters. Our observing strategy involved acquiring 3–10 s exposures in a dithered pattern consisting of four frames with vertical and horizontal offsets of ∼22 and ∼9 arcsec, respectively.

Data reduction and calibration procedures are summarized in Appendix A. Table 1 gives the dates, integration times and calibration parameters for each observation. Fig. 2 shows the ISAAC J-band image of NGC 4438 after flat-fielding, bad-pixel correction, and sky and bias subtraction.

Only the central region of the field (inner 40 arcsec) has a symmetric point-spread function (PSF). The outskirts of the array show extended tails due to optical aberrations. In this central region, we report a seeing of ∼0.5 arcsec for the NB filters, while for the broad-band filters we report a seeing of 0.6–0.8 arcsec (see Table 1).

2.1.1 Complementary imaging data

We also observed NGC 4438 with the Thermal Infrared Multimode Instrument 2 (TIMMI2) camera on the ESO 3.6-m telescope on
μCμ × RWm archive located at the Cana-

60 arcsec coordinates of the nucleus, with a 5 arcsec rms positional

Aμy and BrK−μ2098–2110 2009 RAS, MNRAS

2.12 B J × Seeing

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images, broad-bands F450W (from 29 July 2018

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of NGC 4438 for position angles:

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h-band ISAAC image

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65. The object is

m, which is free of emission lines. Yet our

aligned chopping and nodding strategy, with a throw of 30 arcsec

north–south, fits one of the negative images on the array. The pres-

ence of the chopped image confirms our detection. We enhanced

the signal-to-noise ratio of our image by smoothing with a Gaussian

kernel, with a dispersion of 2 pixels, or 0.6 arcsec. Flux calibration

was obtained by comparison with HD81797, with an 11.9 μm flux
density of 100.57 Jy. By fitting an elliptical Gaussian to the stan-

dard star we infer an angular resolution of 0.76

× 0.71 arcsec² FHWM. After smoothing, the resolution of the image in Fig. 10 is

about 0.96 arcsec. We set the astrometry by tying the centroid of the

11.9 μm emission to the HST coordinates for the nucleus.

We complemented the infrared data with recalibrated WFPC2

HST images, broad-bands F450W (B), F675 (R) and F814W (I).

We retrieved these data from the HST archive located at the Cana-
dian Astrophysics Data Centre (CADC). The CADC pipeline recal-

ibrates the images with up-to-date calibration files. The details of

these observations are described by Kenney & Yale (2002). Since

the pixels covering the nuclear emission were saturated in R and I

images, we used only the B-band image to carry out the photometry

of the nucleus.

2.2 Medium-resolution NIR spectroscopy

NIR spectra of NGC 4438 were obtained with ISAAC at VLT on

2003 March–April. We acquired medium resolution spectra at cen-

tral wavelengths of 1.274, 2.170 and 2.310 μm, and slit widths of

0.3 and 0.6 arcsec. The list of observations, filters, position an-
gles, spectral domains, resolutions and slit widths can be found in

Table 2. Fig. 2 shows some of the slit positions overlaid on the

J-band ISAAC image.

The sky background (including OH skylines) was removed by
differencing along the slit, with nod throws of 30 arcsec (or 30 arcsec

in the case of standard stars). Wavelength calibration was obtained

by comparison with arc lamps. The spectra were extracted in 0.74

arcsec centred on the peak of emission. Telluric absorption spectra

and flux density calibration were obtained by observing the early-
type star HD115709 (spectral type A1IV) and comparing with a

blackbody spectrum. Stellar absorption features at Paβ and Bγ were

accounted for by fitting Voigt profiles in a total wavelength

range of 0.015 μm in the vicinity of the stellar absorption lines.

Samples of the reduced spectra, centred at 1.274 and 2.170 μm, are

shown in Fig. 3.

Flat-fielding was hampered by short-term variations in the CCD

pixel gains. The observatory pipeline flat fields could not suppress

the low-level features on scales of 0.005 μm seen in the spectra

of Fig. 3. The features under ~2 × 10⁻¹⁵ W m⁻² μm⁻¹ were

not reproduced in different exposures, which suggests flat-fielding

artefacts. Try as we might we could not improve on the pipeline

flats. We treat the low-level artefacts as noise, so that the depth of

the spectroscopy did not meet our expectations. The ISAAC NIR

spectroscopy is none the less informative on the kinematics of the

CO-band heads, [Fe ii] 1.26 μm and H₂ 2.12 μm.

| Date          | Filter | Integration (s) | Zero-point (mag) | Aμa (mag) | Seeingb (arcsec) |
|---------------|--------|-----------------|------------------|-----------|------------------|
| 2003 April 14 | J      | 400             | 24.85            | 0.025     | 0.86             |
| 2003 April 14 | H      | 400             | 24.31            | 0.016     | 0.62             |
| 2003 January 13 | Ks  | 284             | 24.12            | 0.010     | 0.58             |
| 2003 April 14 |        | 1.26            | 21.88            | –         | 0.69             |
| 2003 April 14 |        | 1.28            | 21.69            | –         | 0.56             |
| 2003 January 13 |     | 2.07            | 21.62            | –         | 0.55             |
| 2003 January 14 |     | 2.13            | 21.80            | –         | 0.57             |
| 2003 January 13 |     | 2.17            | 21.76            | –         | 0.51             |

aForeground extinction (see Section 3.1).

bEffective seeing at the observed wavelength, given by the FWHM of the best-fitting Gaussian

profile.

Figure 2. Overlay of the ISAAC 120-arcsec slit on the J-band ISAAC image

of NGC 4438 for position angles: +17.25, −37.55, −57.65. Convention is

positive position angle from north to east. The x- and y-axes are east and

north offsets in arcsec from the nucleus at J2000 RA 12h27m45.6 and J2000

Dec. +13° 00′ 32″ (from HST astrometry).
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ISAAC NIR spectra of the nucleus of NGC 4438. Top spectrum
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Good. No PAHs.
2098–2110
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Good. CO band heads
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SK
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+107.25
Good. CO band heads
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2.11–2.23
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4400
2 × 300
−57.65
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J
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−57.65 Regular. Resolved [Fe II] emission
2098–2110
J
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−37.55, +17.25, +76.65 Good. Resolved [Fe II] emission for PA−37.55
2098–2110
SK
2.11–2.23
0.3
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2 × 500
−37.55, +17.25, +76.65 Regular. Resolved H2 emission for PA −37.55

2.3 Low-resolution spectroscopy

We acquired a low-resolution L-band (3.8 μm) spectrum at PA
+56.94, in 7 ABBA nodding cycles, between positions A and B
along the slit, for a total integration time of 1 h (with individual
DITs of 0.935 s and four exposures, a chop throw of 20 arcsec, and
a chopping frequency of 0.11 Hz). The spectrum shows a continuum
rising towards longer wavelengths. This L-band spectrum does
not show any spatially resolved features. The flux density in the
collapsed 0.6 arcsec slit is 3 × 10−15 W m−2 μm−1 at 2.8 μm, and
6 × 10−15 W m−2 μm−1 at 4.0 μm. The noise varies as a function
of wavelength between 10−13−10−14 W m−2 μm−1. This spectrum
shows no evidence of the presence of polycyclic aromatic hydro-
carbons (PAHs) emission in NGC 4438.

3 RESULTS

3.1 Extinction estimates

A consequence of the dependence of interstellar extinction on wave-
length is that the NIR imaging often reveals surprising morphologi-
cal differences when compared to optical observations (see Cardelli,
Clayton & Mathis 1989, for a description of the Galactic extinction
law). Nuclear extinction estimates are very uncertain in NGC 4438.
The Balmer decrement Hα/Hβ gives AV ≈ 3.4 (using the extinction
law from Cardelli et al. 1989), but this represents a luminosity-
weighted average over the central 2 × 4 arcsec2 extraction aperture
of the low-resolution ground-based spectroscopy reported by Ho
et al. (1997), and also a lower limit to the true extinction.

In order to further investigate the spatial distribution of the dust
in the system we generated an extinction map (see Fig. 4). This was
done by transforming the J − K colour image into a colour excess
map, E(J − K). We assumed a flat and constant stellar population,
as expected for bulges of spirals, with E(J − K) = 0.8 (calculated
over a 7 × 7 arcsec2 aperture in a region devoid of structure).
The colour excess map E(J − K) and the column of hydrogen nuclei NH
are related by NH/E(J − K) = 1.1 × 1022 cm−2 mag−1, assuming
a Galactic gas-to-dust ratio and RV = 3.1 (Tokunaga 2000). We
inferred a mean colour excess E(J − K) = 0.40 for an aperture
matched with the 2 × 4 arcsec2 used by Ho et al. (1997). Using
the standard IR interstellar reddening law (Cardelli et al. 1989),
it implies a visible colour excess E(B − V) = 0.7, which is
fully consistent with the colour excess reported by Ho et al. (1997),
of E(B − V) = 0.61. As revealed by the presence of strong dust
danes, the nuclear extinction is highly variable towards the central
hundred parsecs (Kenney & Yale 2002). The spatial distribution
of extinction and dust is shown in Fig. 4. The lower edge of the
Hα bubble emission is coincident with bands of strong extinction.
These region of high extinction seem to be surrounding the nucleus
(given by the peak of Hα emission), with a peak of AV ≈ 4.4 mag
at around 1 arcsec east of the nucleus.

The measured colour excess implies an average hydrogen column
density NH = 2.7 × 1021 cm−2 at the base of the NW bubble (shown
in Fig. 4), and a mean column NH = 1.2 × 1021 cm−2 for the rest
of the NW bubble (using the total to selective absorption from
3.2 Maps of extended emission

Fig. 5 shows the $[\text{Fe II}]$ 1.26 $\mu$m and $H_2$ 2.122 $\mu$m maps of line emission, after subtracting the continuum emission. The fact that there is some negative emission at the base of the NW bubble implies that there is some Pa$\beta$ emission contaminating the continuum image. We are certain that this contamination does not affect the NW extended emission since the spectrum shows no trace of Pa$\beta$ emission at a noise level of $1\sigma = 1.06 \times 10^{-16}$ W m$^{-2}$ $\mu$m$^{-1}$, when the slit is aligned with the NW bubble (PA $\sim 37.55$ and $-57.65$, see Fig. 3). In the case of $H_2$ emission, we used a scaled version of the $K_s$ broad-band image to subtract the continuum. The presence of this strong $[\text{Fe II}]$ emission is consistent with LINER spectroscopic surveys (Larkin et al. 1998), confirming the LINER classification of the NGC 4438’s nuclear region.

The outflow shells are very asymmetric in the optical lines and the radio and X-ray continuum. This provides further evidence that the outflow shells are intrinsically different, and that the observed dissimilarities are not due principally to extinction. In the NIR, we have detected only the NW outflow, with no trace of the south-eastern (SE) outflow neither in $[\text{Fe II}]$ nor $H_2$ emission.

3.2.1 $[\text{Fe II}]$ extended emission

The emission-line map shown in Fig. 5(a) indicates that $[\text{Fe II}]$ emission is coincident with $HST H_{\alpha}+[N \text{ II}]$ emission-line detected by Kenney & Yale (2002), Chandra X-ray emission reported by Machacek et al. (2004), and the complex radio continuum blob A described by Hummel & Saikia (1991). Emission from a counter-shell in the SE region is clearly detected in $H_{\alpha}+[N \text{ II}]$ and radio (see Kenney & Yale 2002), but is much fainter, and is located much further from the nucleus (9 versus 4 arcsec) than the much-brighter NW shell. Fig. 5 also reveals a lack of this SE emission. This is because the SE emission is 15 times fainter than the NW component in $H_{\alpha}+[N \text{ II}]$ (Kenney & Yale 2002), and even weaker in the X-ray (a factor of 32 lower counts than the NW shell; Machacek et al. 2004). Also, most of the bubble-like emission seen in $H_{\alpha}+[N \text{ II}]$ corresponds to $[N \text{ II}]$ emission since $H_{\alpha}$ is about two times weaker compared to $[N \text{ II}]$. This column density is in reasonable concordance with the values reported by Machacek, Jones & Forman (2004). Machacek et al. (2004) obtained a best-fitting column density of $\sim 2 \times 10^{21}$ cm$^{-2}$ from modelling of the X-ray spectra of the NW bubble. The uncertainties in our extinction estimates are mainly due to variations in the stellar population near the nucleus.
than ionized nitrogen emission according to Fig. 1. The bright H\textsc{ii} regions, detected in \textup{H}\textalpha+[\textup{N}\textsc{ii}] emission 8 arcsec towards the south of the nucleus by Kenney & Yale (2002), do not appear neither in Pa\textbeta or [Fe\textsc{ii}] emission nor in X-ray emission (Machacek et al. 2004).

In AGN galaxies, the [Fe\textsc{ii}] emission is thought to arise from the region radiating narrow line emission (Mouri, Kawara & Taniguchi 2000; Riffel et al. 2006). Such regions in AGN can be produced either as a result of photoionization by a nuclear source, including X-ray heating from the central AGN, or via shock excitation by radio jets (Rodríguez-Ardila et al. 2005; Riffel et al. 2006). The dominant excitation mechanism of the [Fe\textsc{ii}] emission is still under debate. Simpson et al. (1996) have argued that photoionization is the dominant excitation mechanism of [Fe\textsc{ii}] and that shocks by radio jets account for only about 20 per cent of the emission in Seyfert galaxies. Rodríguez-Ardila et al. (2005) have shown that the [Fe\textsc{ii}]/Pa\textbeta ratio is a good indicator of the relative contribution of photoionization and shocks, since [Fe\textsc{ii}] seems to be more tightly correlated with the radio emission than hydrogen recombination lines in AGN (Simpson et al. 1996).

Radio maps of NGC 4438 presented by Hummel & Saikia (1991) show extended emission, with a shell-like morphology, that is well aligned with \textup{H}\textalpha and [\textup{N}\textsc{ii}] (see figs 3 and 4 in Kenney & Yale 2002), and therefore also spatially coincident with [Fe\textsc{ii}]. This morphological correlation, along with the non-detection of extended Pa\beta emission in our spectra of the NW bubble, may imply that shock excitation by radio jets contributes to an important fraction of the [Fe\textsc{ii}] emission in NGC 4438.

3.2.2 \textit{H}_2 extended emission

Molecular hydrogen emission is present in many host galaxies of AGNs (Rodríguez-Ardila et al. 2005; Riffel et al. 2008; Riffel, Storchi-Bergmann & McGregor 2009). In the traditional AGN picture, a dusty torus shields the \textit{H}_2 gas from the dissociating AGN radiation field. The \textit{H}_2 emission in NGC 4438 seen in Fig. 5(b) could also be associated with the central AGN engine but it does not seem to trace the NLR gas (Rodríguez-Ardila et al. 2005). As it can be seen in Fig. 5, the molecular hydrogen is distributed only in the inner few hundred parsecs. The \textit{H}_2 emission is much stronger on the north side of the bubble than on the south side. Fig. 5(b) shows that most of the molecular hydrogen gas is concentrated towards the circumnuclear region tracing the presence of a possible dusty torus, as in the case of NGC 3727 (Rodríguez-Ardila et al. 2005) or NGC 4051 (Riffel et al. 2008). Also, some \textit{H}_2 emission extending towards the NW bubble can be seen in our observations.

The position–velocity maps depicted in Fig. 6 show that the kinematics of the [Fe\textsc{ii}] and the \textit{H}_2 emitting gas are distinct. Furthermore, the nuclear [Fe\textsc{ii}] line is broader than the \textit{H}_2 line. As measured from the nuclear spectra shown in Fig. 3, FWHM of the [Fe\textsc{ii}] and \textit{H}_2 \lambda2.12\mu m lines are 415 and 270 km s^{-1}, respectively. This implies that the [Fe\textsc{ii}] is originating from a kinematically more disturbed gas than the \textit{H}_2 emitting gas, which is in agreement with previous observations of other active galaxies, such as NGC 2110 (Storchi-Bergmann et al. 1999) and NGC 4051 (Riffel et al. 2008). A possible interpretation for this is that the \textit{H}_2 emitting gas is more restricted to the galactic plane, perpendicular to the radio jets, while the [Fe\textsc{ii}] emitting gas extends to higher latitudes from the galactic plane (Storchi-Bergmann et al. 1999; Riffel et al. 2008). These results suggest that the \textit{H}_2 excitation is likely to be dominated by X-ray heating from the central AGN.

3.2.3 Pa\beta extended emission

Fig. 5(a) also shows a negative arc to the east of the nucleus, perpendicular to the NW shell. In this arc Pa\beta is stronger than the [Fe\textsc{ii}] emission. The distance between the nucleus and the arc is about 0.5 arcsec (~35 pc), which is much larger than the values pointed out for the radius of the putative torus. These values are typically smaller than 5 pc (see, e.g., Jaffe et al. 2004; Minezaki et al. 2004; Riffel et al. 2009). A possible interpretation for this emission is
that it might be associated with circumnuclear star formation in the outer parts of the torus.

The circumnuclear region seen in negative in Fig. 5(a) has a Paβ flux density of 0.5 mJy (integrated over the arc-shaped feature), which corresponds to a Paβ luminosity of $3.6 \times 10^{40}$ erg s$^{-1}$. If this emission has a starburst origin and we assume solar abundances, and a Salpeter initial mass function ($\psi \propto M^{-2.35}$) with an upper mass cut-off of 100 M$_\odot$, we can estimate the star formation rate (SFR) in the arc feature. Kennicutt (1998) find by extrapolation: SFR (M$_\odot$ yr$^{-1}$) = $7.9 \times 10^{-45} L$(Hα) (erg s$^{-1}$), computed for Case B recombination at $T_e = 10^4 K$. Under these conditions the SFR as a function of Paβ luminosity is

$$\text{SFR}(\text{M}_\odot \text{yr}^{-1}) = 1.4 \times 10^{-41} L(\text{Paβ}) \text{ (erg s}^{-1}),$$  \hspace{1cm} (1)

for $j_{\text{Hα}}/j_{\text{Paβ}} = 17.6$, where $j$ is the emissivity of the line (Storey & Hummer 1995). The extinction-corrected nuclear SFR, using a central extinction $A_V$ of 4 mag, is 1 M$_\odot$ yr$^{-1}$. It represents an overestimated SFR in the circumnuclear region because this emission could include a contribution from the AGN, due to gas that has been ionized by an accreting black hole. For a global description of the star formation history of NGC 4438 as a whole see Boselli et al. (2005).

### 3.3 CO-band stellar kinematics

NGC 4438 is an inclined large spiral galaxy and its kinematics are undoubtedly difficult to study mainly due to the multiplicity of components that build up spiral galaxies. Moreover, NGC 4438’s highly disturbed morphology and the presence of dust make the inference of kinematic measurements a difficult task. On the positive side, its inclined disc permits a relatively simple identification of the direction which might be expected to define one of the principal axes of the bulge.

**CO-band stellar line-of-sight (LOS) kinematics along the minor axis (PA = +107.5) were derived by fitting the galaxy spectra (see Fig. 7)** with a linear combination of template spectra chosen from the Gemini NIR spectral templates library.$^1$ Stellar templates were re-binned to the spectral resolution of the galaxy spectra (15.47 km s$^{-1}$).

Figure 7. Medium-resolution spectrum centred at 2.310 µm with a slits of 0.74 arcsec. The red line represents the best galaxy model fitted by pPXF (see text) as a linear combination of template spectra.

![Figure 7](https://example.com/figure7.png)

Figure 8. LOS stellar velocity dispersion ($\sigma$) as a function of distance along the minor-axis of the galaxy. The LOS velocity dispersion reaches a maximum at the nucleus of the galaxy with $\sigma_{\text{max}} \sim 180$ km s$^{-1}$.

![Figure 8](https://example.com/figure8.png)

$^1$ See NIR resources at: http://www.gemini.edu/sciops/instruments/
Table 3. Best NGC 4438 galaxy structural parameters.

| Filter | $\Delta$ | $q$  | $c$  | $\alpha$ | $n$  | $R_e$ | $R_h$ | $I_e$ | $r_0$ | $I_0$ | $n'$ | $R_e'$ | $I_e'$ | $L_{\text{tot}}$ | $\log M_{bh}$ | $\log M_{bh}(n)$ |
|--------|---------|------|------|----------|------|-------|-------|-------|-------|-------|------|--------|-------|--------------|-------------|---------------|
| J      | 30      | 0.57 | 1.10 | 68.3     | 1.65 | 3.88  |        | 71.76 | 13.46 | 42.65 | 1.75  | $\sim 0$ | 572.63 | 27.7         | 7.19          | 6.90 $\pm$ 0.45 |
| H      | 30      | 0.57 | 1.14 | 68.4     | 1.47 | 3.53  |        | 94.76 | 12.77 | 57.08 | 1.93  | $\sim 0$ | 502.12 | 21.8         | 6.97          | 6.68 $\pm$ 0.45 |
| Ks     | 30      | 0.57 | 1.13 | 68.7     | 1.52 | 3.49  |        | 73.39 | 12.86 | 41.34 | 1.71  | $\sim 0$ | 570.92 | 13.0         | 6.66          | 6.75 $\pm$ 0.45 |
| B      | 30      | 0.50 | 1.20 | 68.9     | 0.80 | 2.50  |        | 23.00 | 8.70  | 30.00 | 1.70  | 0.20  | 154.00 | 7.56         | –             | –             |

Notes – (1) Filter name. (2) Angular size of the fitted region. (3) & (4) generalised ellipticity parameters. (5) Inclination angle in $^\circ$. (6)–(10) are the Sèrsic structural parameters for the bulge, $R_e$ and $R_h$ are in units of arcsec. (11)–(13) are the Sèrsic structural parameters for the nuclear source. (14) Total bulge luminosity in units of $10^{42}$ erg s$^{-1}$, calculated from equation (B3). (15) Black hole masses obtained from the $M_{bh}$–luminosity density relation (Marconi & Hunt 2003). (16) Black hole masses obtained from the $M_{bh}$–$n$ relation (Graham & Driver 2007), the errors are estimated using the intrinsic uncertainties in the Graham & Driver (2007) relation. All radii are given in arcsec, the intensity units are MJy sr$^{-1}$ and the black hole masses are expressed in $M_\odot$.

approach to addressing this question consists of modelling the stellar component by fitting the bulge with a $r^{1/n}$ Sèrsic law, and the outer region (disc) with an exponential profile. The nuclear component will be a priori represented by a point source at the centre of the galaxy. The main advantage of this approach is that it let us identify a nucleus over the stellar contribution, whereas a non-decomposition approach would try to reproduce all the profile without giving back information about separate components. The universality of the Sèrsic plus exponential disc decomposition allows us to compare with other objects. A detailed description of the surface brightness model, as well as the optimisation algorithm can be found in Appendix B.

4.2 Application to the NIR ISAAC data

We fitted the nuclear region ($30 \times 30$ arcsec$^2$) of NGC 4438 with parametric functions, as described in Appendix B. The model is the sum of three components: a bulge, a disc and a compact source. The dust features present near the central region have been taken into account by correcting the images using the extinction map (see Fig. 4).

The best-fitting structural parameters for each filter are summarized in Table 3. The best fit is always obtained with $n$ close to 1.7 and $R_e \sim 3$ arcsec for the bulge component present at NIR wavelengths (see nomenclature in Appendix B). The ellipticity and shape of the isophotes are quite constant with increasing radius, with an ellipticity $e = 0.5$ and slightly discy isophotes ($c = 1.2$, see Appendix B).

Since the integrated flux density presented in Peng et al. (2002) is undefined in the case of ‘discy’ isophotes, we calculated a general expression for the integrated Sèrsic profile flux density, in generalised elliptical geometry, including the case of ‘discy’ isophotes (equation B3). The integrated luminosities of the bulge were computed from the flux densities integrated over all radii.

The result of the two-dimensional fit for the $J$ filter is presented in Fig. 9. The left-hand panel shows a cut along the major axis of the galaxy (dashed curve), the model (solid curve) and its components: bulge (dotted curve), disc (dash–dot–dot curve) and the nuclear component (dash–dot curve). That figure shows an excellent agreement between the model and the galaxy’s light distribution. In this central region, we can see a conspicuous point-source standing out of the bulge. However, galaxies with power-law profiles may show substantial differences along the major and minor axis, due to

Figure 9. Results of the two-dimensional decomposition of NGC 4438 (see text). Left-hand panel: semimajor axis cut to the central 3 arcsec. The dashed line is the dereddened galaxy profile. Right-hand panel: Surface brightness azimuthally averaged over a radial elliptical annulus (points) of width $\Delta r \sim 0.2$ arcsec, with $r$ defined by equation (B1) (axes are in logarithm scale).
isophote twists or ellipticity. For this reason, the right-hand panel shows the surface brightness azimuthally averaged along a radial elliptical annulus; this panel also shows an excellent match between model and data at large radii.

We find evidence for a nuclear point-source unresolved at 0.8 arcsec resolution (see Fig. 9) with $M_K = -18.7$ and $J - K = 0.69$. Its extinction-corrected NIR integrated fluxes in a 3 arcsec aperture for each band are listed in Table 4. The computed bulge luminosity in each broad-band is listed in Table 3. A very similar system was studied by Peng et al. (2002), who found a nuclear point source embedded in NGC 4278, which is an elliptical Seyfert galaxy, also with a LINER nucleus.

4.3 Application to the HST–WFPC2 data

Since the HST B-band image shows much more structure than the NIR data (due to extinction being more severe at shorter wavelengths), we followed two different approaches in order to perform the photometry of the nucleus. The first approach was similar to the one used for the NIR data, i.e. fitting a Sérsic bulge plus an exponential disc and a nuclear source. The nuclear source was represented by an extra Sérsic profile, since the central source in the B-band image is clearly resolved. The result was a less prominent bulge in the optical than in the NIR. In the optical case, the surface brightness is well represented by a bulge with $n = 0.8$ and a compact source well-fitted by a steeper Sérsic component with $n = 1.7$ and $R_e = 0.2$ arcsec, i.e., a resolved nuclear source of approximately 16 pc in size. An $n$ value of 0.8 seems very low for a bulge of a spiral and it may not represent the real bulge surface distribution, this is probably because of the severe obscuring effect of dust at those wavelengths.

The second approach consisted of modelling the structure of the central $2 \times 2$ arcsec$^2$ in the B-band image with a base of Legendre polynomials $P_l(x)$ and $P_k(y)$, both at order $l, k = 6$, in order to get accurate photometry of the nucleus. We added a resolved compact source, represented by $F_0 \delta(x_{cen}, y_{cen})$ convolved with a Gaussian of FWHM = 0.4 arcsec. The free parameters were the $(l + 1) \times (k + 1)$ Legendre coefficients, the centroid of the compact-source ($x_{cen}, y_{cen}$), the FWHM of the nuclear source, and the central intensity $F_0$. The result was similar to the NIR case: a resolved compact source with FWHM = 0.4 arcsec, equivalent to 31 pc, appears to stand out of the nuclear region (see Table 4). This approach is fully consistent with the first approach explained above, which also yields a compact source with $R_e = 0.2$ arcsec since FWHM $\sim 2R_e$.

The difference between the NIR and optical parameter values can be explained mainly by the fact that the extinction is more severe in the optical than in the NIR. Also, in spiral galaxies the bulge is mainly composed of late-type stars, hence yielding a more prominent bulge in the NIR than in the optical. Photometry of the extracted nuclear source yields $M_B \sim -12.24$ mag.

5 DISCUSSION

5.1 Spectral energy distribution

NGC 4438 is classified as a LINER 1.9 or a ‘dwarf’ Seyfert 2 galaxy on the basis of broad Hα emission (Ho et al. 1997; Kenney & Yale 2002). We constructed the NGC 4438 SED of the non-stellar component using data from radio ($\nu = 4.86 \times 10^9$ Hz) to hard X-rays ($\nu = 1.7 \times 10^{18}$ Hz).

The NIR data ($\log (\nu/Hz) \sim 14$) were obtained from the surface brightness decomposition presented in Section 4. The AGN component photometry is given in Table 4, and it was computed by integrating the residual image over a circular aperture of radius 4.5 arcsec centred on the nucleus.

The thermal infrared [$\log (\nu/Hz) \sim 13.4$] photometry of the nuclear source was extracted over a 4.5 arcsec circular aperture in the TIMMI2 NB 11.9 μm image (see Fig. 10). The result was a mid-IR flux density of $0.20 \pm 0.04$ Jy. Instead of a compact nuclear source, Fig. 10 shows that the thermal emission is spatially extended over 3.5 arcsec, which at the Virgo distance corresponds to 270 pc. Thus, the nucleus and a circumnuclear dusty arc dominate the mid-IR continuum emission.

The soft [$\log (\nu/Hz) = 17.6$] and hard [$\log (\nu/Hz) = 18.2$] X-ray counterparts were obtained from Chandra data reported in table 4 of Machacek et al. (2004), without any absorption correction. The radio continuum [$\log (\nu/Hz) = 9.3$] data were obtained from Hummel & Saikia (1991). This measurement was computed by integrating the extended emission over a rectangle of sides $2 \times 5$ arcsec. It gives $1.5 \pm 0.3$ mJy. This value corresponds to an upper limit since
The nucleus of the galaxy suggests that the flows in the accretion disc are advection dominated.

the nucleus was not clearly detected, and it may contain emission from the NW and SE outflows.

Fig. 11 shows the SED of NGC 4438. The solid line is a simple theoretical SED taken from Siebenmorgen et al. (2004), which is based on three parameters: a dusty torus with radius 125 pc, an average visual extinction of 4 mag and a compact source with bolometric luminosity $L_{\text{bol}} = 5.6 \times 10^{10} L_{\odot}$, which does not represent NGC 4438’s bolometric luminosity because of discrepancy between with the model in the X-ray region of the spectrum. The AGN is modelled as a power law with monochromatic luminosity $L(\nu) \propto \nu^{-0.7}$ in the wavelength range from 10 Å to 2 µm. The dust is composed of carbon and silicate grains with radii between 300 and 2400 Å, graphites of radius 10 Å and small and large PAH components. Fig. 11 also shows a good match between both NIR and visible data with the theoretical SED. However, this model is unable to fit the X-ray data. The sub-Eddington X-ray emission $L_X \sim 10^{-6} L_{\text{Edd}}$ (where $L_{\text{Edd}} \sim 10^{45}$ erg s$^{-1}$ is the Eddington luminosity for a black hole with mass $10^7 M_{\odot}$) in both, the soft and hard bands, suggests that the accretion flows are advection dominated (Narayan, McClintock & Yi 1996; Kenney & Yale 2002; Machacek, Jones & Forman 2004).

5.2 Outflows and energetics

From ultraviolet observations, Boselli et al. (2005) found that the star formation in the main body of NGC 4438 is very weak, and is mainly composed of old stars, without signs of recent starbursts. Our estimation of the visual extinction towards the nucleus of $A_V \sim 4$ corresponds to an extinction of 3.3 mag at Hα (Cardelli et al. 1989), implying an extinction-corrected SFR of 0.08 M$_{\odot}$ yr$^{-1}$ for the nucleus. On the other hand, the SFRs inferred from the extinction-corrected Pa$\delta$ emission is 1 M$_{\odot}$ yr$^{-1}$ and corresponds to the circumnuclear region seen as an arc in Fig. 5(a). These two estimates correspond to upper limits since we do not know how much of the line emission arises from H$\alpha$ regions near the nucleus.

The velocity of the north-western outflow can be estimated from the spectrum shown in Fig. 6(a). The width of the line contains contributions from both random motions and bulk velocity. The FWHM of the [Fe II] line at 3–4 arcsec from the nucleus, extracted from a 2 arcsec aperture is measured to be $\sim 350$ km s$^{-1}$ while the mean [Fe II] velocity 2 arcsec from the nucleus (at the bottom of distinct blob) is closer to 500 km s$^{-1}$ (see Fig. 6). In fact, the mean velocity as a function of distance from the nucleus decreases from $\sim 500$ km s$^{-1}$ at 2 arcsec to $\sim 350$ km s$^{-1}$ at 2.5 arcsec. This seems consistent with an expanding bubble model since if the observed expansion velocity at the outer edge of the bubble corresponds to a lower LOS velocity than at the middle of the bubble, due to projection effects. Hence, we adopt a speed of 500 km s$^{-1}$ as a reasonable value for the expansion velocity, which is a faster outflow than the one assumed by Kenney & Yale (2002) of 300 km s$^{-1}$.

Kenney & Yale (2002) calculated the mass of ionized gas from the H$\alpha$ luminosity, which corresponds to $3.5 \times 10^4 M_{\odot}$ for an electron density of 420 cm$^{-3}$ (measured from the [S II] $\lambda\lambda 6716/6731$ doublet ratio). This new estimate of the outflow velocity increments the kinetic energy by a factor of $\sim 3$, yielding an injected kinetic energy into the halo of the galaxy of $> 10^{42}$ erg. This is a lower limit since only ionized gas is included in the calculation and we know that there is molecular gas also present in the NW bubble [see Fig. 5(b)]. The large amount of kinetic energy carried by the north-western outflow along with the weak nuclear star formation, suggests that an AGN central engine is responsible for much of the optical and NIR line and continuum emission, and not a compact starburst (Kenney & Yale 2002).

5.3 NGC 4438 colours

The NIR colours of the nucleus of NGC 4438 mainly have contributions from: a bulge of late-type stars; a non-stellar nuclear source; re-radiation from hot dust and reddening (Kotilainen et al. 1992). We measured the colours of each surface brightness component in an aperture of 3 arcsec, in order to compare with other works (there was no substantial variation using an aperture of 8 arcsec). Normal (inactive) spiral galaxies have colours of $0.6 < J - H < 0.9$ and $H - K_s < 0.3$ (Kotilainen et al. 1992; Fischer et al. 2006). The stellar colours of NGC 4438, $J - H = 0.7$ and $H - K_s = -0.10$, are clearly in the region occupied by normal spiral nuclei. As expected for LINERs and Seyfert 1 galaxies (see two-colour diagrams in Kotilainen 1993; Forbes et al. 1992), the non-stellar colour of NGC 4438 is located in between the regions of AGN and inactive galaxies, shifting the colours according to a reddened vector of $A_V \sim 3 - 4$. Therefore, the NIR stellar colours do not show evidence for starburst, in agreement with the ultraviolet observation of Boselli et al. (2005). This seems to be inconsistent with the relatively high SFR estimated from Pa$\delta$ emission for the circumnuclear region (see Section 3.2.3), which would imply that this emission is not due to star formation but to the densest gas near the nucleus being photoionized by the central AGN.

5.4 Black hole mass

Ferrarese et al. (2006) pointed out that a more or less a constant fraction of a galaxy bulge mass ends up as a central massive object either a stellar nucleus or a supermassive black hole. The evidence discussed in Section 3.3 could suggest the presence of a black hole, although the radius of its sphere of influence $R_{BH} \sim 0.1$ arcsec is considerably smaller than our 0.74 arcsec resolution. Ferrarese & Merritt (2000) found that there is a tight correlation between one of the fundamental properties of a galactic bulge, its velocity dispersion $\sigma$, with the mass of its supermassive black holes.
Independently, the same correlation was found by Gebhardt et al. (2000), in the same year. For NGC 4438, we have calculated the luminosity weighted velocity dispersion to be σ = 142 ± 8 km s^{-1} in the central 3 arcsec over the minor-axis, by using the kinematical data (see Fig. 8) and assuming an axial ratio q = 0.57 (see Table 3). The $M_{\text{bulge}} - n$ relation using this value yields a mass for the central black hole of log($M_{\text{bh}}/M_\odot$) = 7.5 ± 1.7.

Recently, Graham & Driver (2007) suggested that there is a fundamental correlation between the Sérsic index $n$, which is a measure of the concentration within the bulge, and the black hole mass. The physical interpretation is that steeper and more concentrated bulges (larger $n$) host more massive black holes. They found a $M_{\text{bh}} - n$ log-quadratic relation using updated black hole masses and power-law indexes. This relation was computed from a sample of 27 galaxies with black hole mass determination from the correlation between stellar velocity dispersion and virial bulge mass. The Sérsic indexes in Graham & Driver (2007) were determined by performing a surface brightness decomposition similar to the one used in this work. The $M_{\text{bh}} - n$ relation is as tight as the well known correlation between the stellar velocity dispersion and the black hole mass (Graham & Driver 2007).

We found a bulge well-represented by a Sérsic index $n = 1.7$. This index implies a black hole with mass log($M_{\text{bh}}/M_\odot$) = 6.70 ± 0.45 for NGC 4438 (for the estimation in each broad-band see Column (16) of Table 3). The errors in the black hole mass were estimated using the intrinsic uncertainties in the Graham & Driver (2007) relation. We did not estimate a black hole mass from the bulge parameters inferred from the B-band image because the bulge is highly obscured by dust. Another estimator of $M_{\text{bh}}$ is the NIR luminosity (Marconi & Hunt 2003), which provides a $M_{\text{bh}}$-bulge relation tighter and less sensitive to extinction than those in the optical. Column (15) of Table 3 lists the computed black hole masses using the NIR luminosity. It can be seen that these methods yield results in reasonable good agreement.

6 CONCLUSIONS

In this paper, we have presented a study of the nuclear source and central environment of the galaxy NGC 4438, based on the results of NIR ISAAC VLT/ANTU imaging and spectroscopy. The main results of this work are as follows.

(i) We have found extended [Fe\textsc{ii}] emission coincident with the NW bubble seen in radio continuum, X-rays and optical emission. The morphological correlation between [Fe\textsc{ii}] and previous radio observations, along with the absence of Pa\textsc{ii} in our spectra of the NW bubble, suggests that shocks (perhaps driven by a radio jet) may be an important source of excitation of [Fe\textsc{ii}] emission.

(ii) Based on our newly (upwardly) revised estimation of the expansion velocity of the bubble, 500 km s^{-1}, and the nuclear SFR estimated from its emission in H\textalpha, which could be up to 0.08 M_\odot yr^{-1}, corrected by the nuclear extinction, we have addressed the question whether the outflow has an AGN or a starburst origin. The large kinetic energy associated with the outflowing gas, $> 10^{44}$ erg, along with the weak star formation suggests that an AGN is more likely to power the outflow.

(iii) The H\textalpha emission map shows strong molecular hydrogen emission around the nucleus which might indicate the presence of a molecular torus.

(iv) Our position-velocity maps showed that the gas emitting H\textalpha is kinematically distinct from the gas radiating [Fe\textsc{ii}] emission. Moreover, the nuclear [Fe\textsc{ii}] line (FWHM ~ 415 km s^{-1}) is broader than the nuclear H\textalpha emission (FWHM ~ 270 km s^{-1}), implying that the [Fe\textsc{ii}] gas is kinematically more disturbed than the H\textalpha gas. Furthermore, the molecular gas seems to be more restricted to the galactic plane, while [Fe\textsc{ii}] extends to higher latitudes from the plane of the galaxy. These results suggest that X-ray heating from a central AGN may be responsible for the excitation of H\textalpha.

(v) We have applied a two-dimensional surface brightness decomposition to the central 30 arcsec of NGC 4438. The best-fitting model consists of three components: a Sérsic bulge with power-law index $n$ ~ 1.7 and $R_e$ ~ 3 arcsec, an exponential disc with $R_{\text{d}}$ ~ 13 arcsec, and a compact nuclear source, resolved in HST with $R_e$ ~ 0.2 arcsec. The model was evaluated in a generalised elliptical surface with discy isophotes and an inclination angle of 69°.

(vi) We have constructed the spectral energy distribution of the nucleus of NGC 4438. It is in agreement with a theoretical SED of an AGN obscured by 4 mag, although the X-rays are underluminous by 6 orders of magnitude (compared to the Eddington luminosity for a 10^5 M_\odot black hole), which can be explained on the basis of advection-dominated accretion flows.

(vii) We have derived CO-band stellar LOS kinematics along the minor axis of the galaxy. The LOS velocity dispersion showed a strong peak on the centre of the galaxy of 177 ± 8 km s^{-1}.

(viii) A black hole mass of log($M_{\text{bh}}/M_\odot$) ~ 7 for the nuclear point source could be inferred from the bulge luminosity, the central velocity dispersion and the Sérsic index $n$.

(ix) We have carried out NIR photometry of the nucleus, finding a point source unresolved by ISAAC at 0.8 arcsec resolution with $M_K = -18.7$ and $J - K = 0.69$. This detection is further evidence that the central source is associated with an AGN rather than a starburst engine.

(x) We report the brightnesses and colours of the various components in the central region. The dereddened stellar colours (bulge and disc) in the nuclear region are typical of an inactive spiral galaxy, and show no evidence for a recent starburst. This is further evident that significant star formation was not triggered in the recent collision with M86.

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REFERENCES

Amico P., Cuby J. G., Devillard N., Jung Y., Lindman C., 2001, ISAAC Data Reduction Guide, V. 1.5. ESO, Garching

Boselli A. et al., 2005, ApJ, 623, L13

Cappellari M., Emsellem E., 2004, PASP, 116, 138

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APPENDIX A: DATA REDUCTION

In this Appendix, we outline the procedures used in the data reduction process, which included bias subtraction, flat fielding, correction of detector defects, cosmic ray removal and overlapping of the dithered frames. The detector has a jump between the two halves of the array, caused by imperfect removing of the zero level offset due to variations in the bias level (Amico et al. 2001, see below).

Flat fielding and bad pixels correction. The twilight flat-field images provided by the observatory were sometimes affected by spurious large-scale gradients (specially in the $K_s$ band). This could be caused by bad ambient conditions, making non-linear effects important (L. Tacconi, private communication). We thus divided the flat field by a smooth approximation of the large-scale variations. The smooth flat field was generated by taking the median of the detector image along the $x$-axis, excluding the outer $\sim$100 columns, which generated a vector column representative of the large-scale variation.

Sky and bias residual subtraction. This is the most important step in the reduction. The sky was obtained immediately after the last object image, pointing the telescope towards a blank region of the sky. The subtraction of the dark current was one of the most important problems to solve, because the dark current is known to be unstable in ISAAC (Amico et al. 2001). The bias level of the detector is a function of the detector integration time and its illumination. The bias level also varies in time, and is more pronounced where the readouts start (i.e. rows 1, 2, and rows 513, 514). Due to this variation we did not apply the dark subtraction, which yielded images containing notable bias residuals. We removed these bias artefacts by performing a linear extrapolation along the array. The procedure was:

1) to isolate regions devoid of extended emission;
2) then, to smooth the regions with a median filter and collapse them along the $x$-axis to obtain single bias residual columns and
3) finally, perform a linear interpolation between the collapsed columns to the entire detector array, generating a smooth bias image.

Dithering. The shifts in the dithered frames were obtained by maximizing the covariation between the images as a function of astrometric offset (at a subpixel level).

Photometric calibration

We acquired a dedicated set of relatively faint standards from the UKIRT telescope system (Hawarden et al. 2001), specifically the stars FS6, FS20 ($J$, $H$ filters) and FS132 ($K_s$ filter). The three standard star observations share a similar dithering pattern as the object observations, and they were reduced following the procedure explained above. The calibration was based on aperture photometry (aperture radius 4.4 arcsec). Table 1 summarizes the computed zero-points. We calibrated the narrowband filters using the corresponding broad-band calibration (as recommended in the ISAAC manual; Amico et al. 2001). No corrections for atmospheric extinction were required because the data were obtained at similar airmass ($\sim 1.4$).

Foreground Galactic extinction obtained from the Schlegel, Finkbeiner & Davis (1998) maps of dust emission, amounts to $E(B - V) = 0.028$. Table 1 summarizes the magnitudes of extinction for each bandpass, computed using $R_V = 3.1$ and the extinction laws of Cardelli et al. (1989).

Photometric uncertainties were estimated as $\sigma_i^2 = \sigma_{\text{rms}}^2 + \sigma_{\text{calib}}^2$. The first term is the rms noise and the second term takes into account the calibration accuracy (10 per cent).

We verified the measured fluxes in our calibrated images using Two Micron All Sky Survey (2MASS). The result was a 2–4 per cent
APPENDIX B: SURFACE BRIGHTNESS PROFILE MODEL

This Appendix gives a detailed description of the surface brightness model used to fit the NGC 4438 light distribution. Our conventions and coordinate systems are shown in Fig. B1. In order to obtain an accurate fit, we constructed an elliptical polar-grid, with the coordinate axis defined by Athanassoula et al. (1990), as follows,

\[ r = \left( |x|^{2/\epsilon} + |y/q|^{2/\epsilon} \right)^{1/2}, \]  

(B1)

where \( q \) is related to the ellipticity by \( \epsilon = 1 - q \). \( c \) is the parameter which allows us to model the generalised elliptical shape: \( c < 1 \) gives box-like ellipses (boxiness), while for \( c > 1 \) we obtain shapes approaching to diamonds (disciness). In general, galaxies are inclined at an angle \( \alpha \), so we need to rotate our \( x \)- and \( y \)-axis using a simple transform; \( X = R(\alpha) X' \), where \( R(\alpha) \) is the rotation matrix (see Fig. B1). The angle \( \alpha \) is defined with respect to the image pixel coordinate system, increasing counterclockwise.

The Sersic (1968) light profile is very useful for modelling elliptical galaxies and steep spiral bulges. It has the form:

\[ I_b(r) = I_e \exp \left\{ -b_n \left[ \left( \frac{r}{R_e} \right)^{1/n} - 1 \right] \right\}, \]  

(B2)

where \( r \) is the generalised elliptical radius (defined in equation B1), \( I_e \) is the intensity at the effective radius \( R_e \) and \( b_n \) is defined such that \( \Gamma'(2n) = 2\Gamma(2n, b_n) \) where \( \Gamma' \) and \( \Gamma \) are the complete and incomplete gamma functions, respectively. Analytical expressions which value the parameter \( b_n \) give \( b_n = 2n - 0.33 \), for \( 0.5 < n < 10 \). Half of the total luminosity predicted by the profile comes from \( r < R_e \). The power-law index \( n \) describes the shape of the light profile. To calculate the total flux of the Sersic profile, we integrated over a generalised elliptical radius \( r \). It gives

\[ F_{\nu} = \frac{2\pi}{\pi} \Gamma(n) R_e^2 \left( \frac{2n}{1-n} \right) \gamma(2n, x) I(q, c), \]  

(B3)

where \( x = b_n (r/R_e)^{1/n} \). The function \( I(q, c) \) is given by

\[ I(q, c) = \frac{2\pi}{\pi} \int_{0}^{\pi/2} \sin \phi \cos \phi^{2-1} \, d\phi. \]  

(B4)

This expression accounts for the generalised-elliptical shape. When \( c \) is greater than \( 2 \) (‘discy’ isophotes) the integral can be written as a beta function of the parameter \( c \) (see equation 8 in Peng et al. 2002).

Since NGC 4438 is a spiral galaxy, an exponential law is needed to fit the galactic disc. It has the form \( I_d(r) = I_0 \exp(-r/R_d) \), where the parameter \( R_d \) is called the disc scale length, \( I_0 \) is the peak of luminosity, and \( r \) is the elliptical radius (equation B1).

A nuclear source can be added at the centre of the galaxy, representing the AGN component, and it may be either a delta function (for a point source) or a Sersic component (for resolved sources).

Finally, the model takes the form:

\[ I(r) = [I_{\text{nuc}}(r) + I_b(r) + I_d(r)] \otimes \text{PSF}, \]  

(B5)

where \( I(r) \) is the surface brightness at a radius \( r \) (defined in equation B1), \( I_{\text{nuc}} \) represents the nuclear source, \( I_b \) and \( I_d \) represent the bulge and disc components, respectively. The symbol \( \otimes \) is the convolution operator.

The set of free parameters are: the nuclear source centroid \( (x_{\text{cen}}, y_{\text{cen}}) \), those related to the elliptical geometry: \( \alpha, q, i \) and \( c \), the Sersic profile power-law index \( n \), the effective radius \( R_e \), the effective intensity \( I_e \); the exponential disc scale length \( R_d \) and central luminosity \( I_0 \); the nuclear source parameters: \( n', R'_e \) and \( I'_e \) (Sersic case) or the central flux density (delta function case).

We found the best-fitting solution by performing a \( \chi^2 \) minimization. The main steps of the two-dimensional fitting are roughly summarized as follows:

1. Select a subimage, centred on the nucleus. Correct by extinction.
2. Generate a model image based on the initial (or new) conditions.
3. Account for the telescope and atmospheric seeing by convolving the model with the characteristic PSF.
4. Evaluate \( \chi^2 \).
5. Iterate from step 2 until convergence is reached.
6. Generate output images: residual image, original galaxy image and model.

This paper has been typeset from a \( \TeX/\LaTeX \) file prepared by the author.