

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

Sebastian Perez,^{1,2†} Simon Casassus,^{1,3} Juan R. Cortés^{1,4}
and Jeffrey D. P. Kenney⁵

¹*Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*

²*University of Oxford, Department of Physics, Keble Road, Oxford OX1 3RH*

³*LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France*

⁴*Joint ALMA Observatory, Casilla El Golf 16-10, Las Condes, Santiago, Chile*

⁵*Department of Astronomy, Yale University, New Haven, USA*

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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 $M_{\text{bh}} - \sigma$ relation, suggests a central black hole mass of $\log(M_{\text{bh}}/M_{\odot}) \sim 7.0$. 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: $[\text{O III}] \lambda 5007/\text{H}\beta < 3$, $[\text{O I}] \lambda 6300/\text{H}\alpha > 0.05$ and $[\text{N II}] \lambda 6583/\text{H}\alpha > 0.5$ (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).

[★]Based on VLT service mode observations (Programme 69.B-0411) and TIMM12 (run 68.D-0432) gathered at the European Southern Observatory, Chile.

†E-mail: s.perez2@physics.ox.ac.uk

The nucleus of NGC 4438 lies at the root of a nuclear bubble, expanding to the north-west (NW), which has been imaged in $H\alpha + [N II]$ 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 $H\alpha$ 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 $H\alpha$ 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 $H\alpha$ photons can, making it possible to detect heavily obscured line-emitting regions. NIR emission lines, such as $[Fe II]$ 1.257 μ m and H_2 2.122 μ m, are less sensitive to extinction than optical lines such as $H\alpha$. 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 ($a^4D_{7/2} - a^6D_{9/2}$ at 1.257 μ m) is the most commonly detected emission-line in LINERs (see also Rodríguez-Ardila et al. 2005). The H_2 line [$1 - 0S(1)$ at 2.122 μ m] is also a common feature. On the other

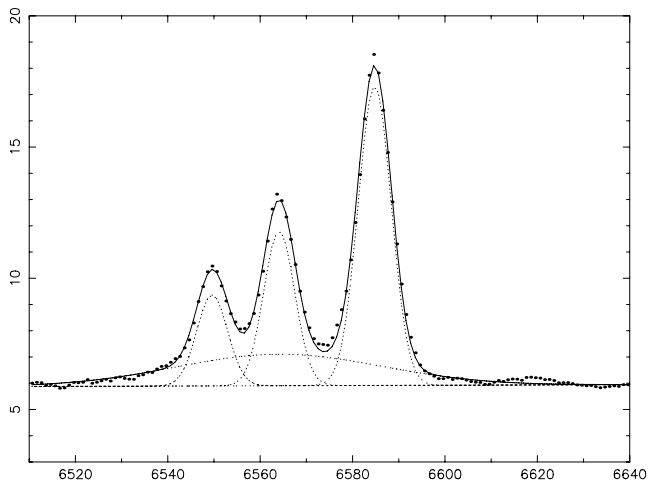


Figure 1. A possible decomposition of $H\alpha$ $\lambda 6562$ and $[N II]$ $\lambda\lambda 6548, 6583$ emission, using the minimum number of components (a linear baseline, three narrow lines and one broad component – or 13 free parameters). The x -axis is wavelength in \AA , while the y -axis is relative intensity. The solid circles are the data points, the solid line is the best-fitting model, and the dotted lines are the contributions from each component. Data courtesy of L. Ho.

hand, the $Pa\beta$ emission line (or $H I$ 3–5 at 1.282 μ m), 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. $Br\gamma$ (or $H I$ 4–7 at 2.166 μ m) 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://pdل.org>; Glazebrook et al. 1997). The stellar kinematics was derived using Interactive Data Language (<http://www.itvis.com/idل/>).

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 arcsec 2 and a pixel scale 0.148 arcsec pixel $^{-1}$. Our data consist of the following broad and narrow-band (NB) filters: J , H , K_s , NB1.26 μ m, NB1.28 μ m, NB2.07 μ m and NB2.13 μ m 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

Table 1. ISAAC imaging observing log and calibration factors.

Date	Filter	Integration (s)	Zero-point (mag)	A_λ ^a (mag)	Seeing ^b (arcsec)
Broad-band data					
2003 April 14	<i>J</i>	400	24.85	0.025	0.86
2003 April 14	<i>H</i>	400	24.31	0.016	0.62
2003 January 13	K_s	284	24.12	0.010	0.58
NB data					
2003 April 14	1.26	600	21.88	–	0.69
2003 April 14	1.28	600	21.69	–	0.56
2003 January 13	2.07	800	21.62	–	0.55
2003 January 14	2.13	800	21.80	–	0.57
2003 January 13	2.17	800	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.

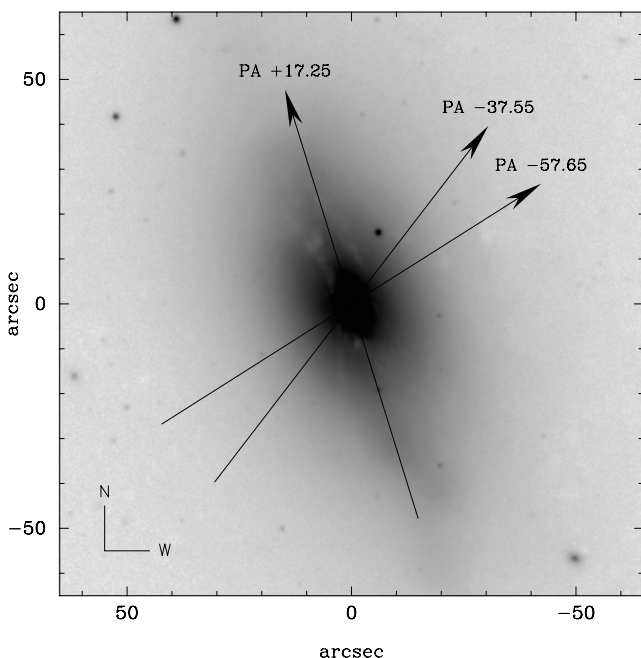


Figure 2. Overlay of the ISAAC 120-arcsec slit on the *J*-band ISAAC image of NGC 4438 for position angles: +17.65, –37.65, –57.65. Convention is positive position angle from north to east. The *x*- and *y*-axes are east and north offsets in arcsec from the nucleus at J2000 RA 12^h27^m45^s.6 and J2000 Dec. +13° 00′ 32″ (from *HST* astrometry).

UTC 2002-01-01T08:50, with a lens scale of 0.3 arcsec pixel⁻¹. The target was acquired in the NB 11.9 μ m filter by blind pointing on the *HST* coordinates of the nucleus, with a 5 arcsec rms positional uncertainty in a field of view of 90 \times 60 arcsec². The object is detected in NB 11.9 μ 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 presence 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 μ m flux density of 100.57 Jy. By fitting an elliptical Gaussian to the standard star we infer an angular resolution of 0.76 \times 0.71 arcsec² FWHM. 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 μ m 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 Canadian Astrophysics Data Centre (CADC). The CADC pipeline recalibrates 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 central wavelengths of 1.274, 2.170 and 2.310 μ m, and slit widths of 0.3 and 0.6 arcsec. The list of observations, filters, position angles, 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 50 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 Pa β and Br γ were accounted for by fitting Voigt profiles in a total wavelength range of 0.015 μ m in the vicinity of the stellar absorption lines. Samples of the reduced spectra, centred at 1.274 and 2.170 μ m, 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 μ m seen in the spectra of Fig. 3. The features under $\sim 2 \times 10^{-15}$ W m⁻² μ m⁻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 μ m and H₂ 2.12 μ m.

Table 2. Spectroscopy observation log.

Date	Filter	Spectral domain (μm)	Slit width (arcsec)	R^a	Integration (s)	PA ^b ($^\circ$)	Notes on quality and spectral features
2002 April 04	SL	2.80–4.00	0.6	600	24 \times 0.94	−57.10	Good. No PAHs.
2002 April 04	SK	2.25–2.37	0.3	8900	2 \times 300	+107.25	Good. CO band heads
2003 February 09	SK	2.11–2.23	0.3	8900	2 \times 300	+107.25	Good. CO band heads
2003 February 09	SK	2.11–2.23	0.6	4400	2 \times 300	−57.65	Bad, fringing
2003 April 14	J	1.25–1.30	0.6	5200	2 \times 600	−57.65	Regular. Resolved [Fe II] emission
2003 May 23	J	1.25–1.30	0.3	10500	2 \times 300	−37.55, +17.25, +76.65	Good. Resolved [Fe II] emission for PA−37.55
2003 May 23	SK	2.11–2.23	0.3	8900	2 \times 500	−37.55, +17.25, +76.65	Regular. Resolved H ₂ emission for PA −37.55

^aSpectral resolution from ISAAC manual.

^bPosition angle on the sky, convention is positive from north to east.

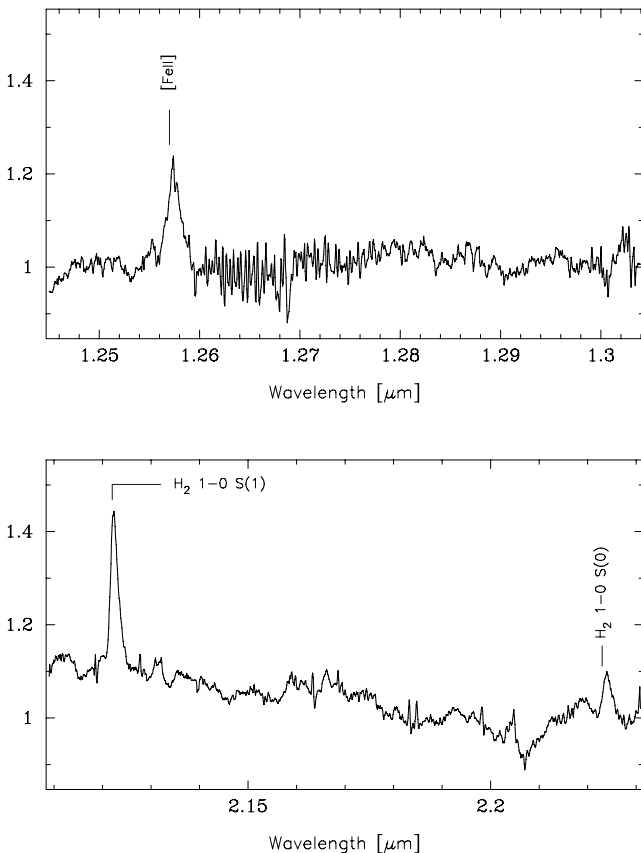


Figure 3. ISAAC NIR spectra of the nucleus of NGC 4438. Top spectrum is centred on 1.274 μm , while the bottom spectrum is centred on 2.170 μm . Top and bottom spectra were acquired with position angles are $-37^\circ 55'$ and $-57^\circ 65'$, respectively. Note the absence of the hydrogen recombination lines, Pa β at 1.28 μm and Br γ at 2.16 μm , in the spectra. Both spectra were extracted from a 0.74 arcsec aperture. Wavelengths are in microns, flux densities are in units of $6.5 \times 10^{-15} \text{ W m}^{-2} \mu\text{m}^{-1}$.

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 $3 \times 10^{-15} \text{ W m}^{-2} \mu\text{m}^{-1}$ at 2.8 μm , and $6 \times 10^{-15} \text{ W m}^{-2} \mu\text{m}^{-1}$ at 4.0 μm . The noise varies as a function of wavelength between 10^{-15} – $10^{-14} \text{ W m}^{-2} \mu\text{m}^{-1}$. This spectrum shows no evidence of the presence of polycyclic aromatic hydrocarbons (PAHs) emission in NGC 4438.

3 RESULTS

3.1 Extinction estimates

A consequence of the dependence of interstellar extinction on wavelength is that the NIR imaging often reveals surprising morphological 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 H α /H β gives $A_V = 3.4$ (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 N_H are related by $N_H/E(J - K) = 1.1 \times 10^{22} \text{ cm}^{-2} \text{ mag}^{-1}$, assuming a Galactic gas-to-dust ratio and $R_V = 3.1$ (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 of $E(B - V) = 0.7$, 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 lanes, 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 H α 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 H α emission), with a peak of $A_V \sim 4.4$ mag at around 1 arcsec east of the nucleus.

The measured colour excess implies an average hydrogen column density $N_H = 2.7 \times 10^{21} \text{ cm}^{-2}$ at the base of the NW bubble (shown in Fig. 4), and a mean column $N_H = 1.2 \times 10^{21} \text{ cm}^{-2}$ for the rest of the NW bubble (using the total to selective absorption from

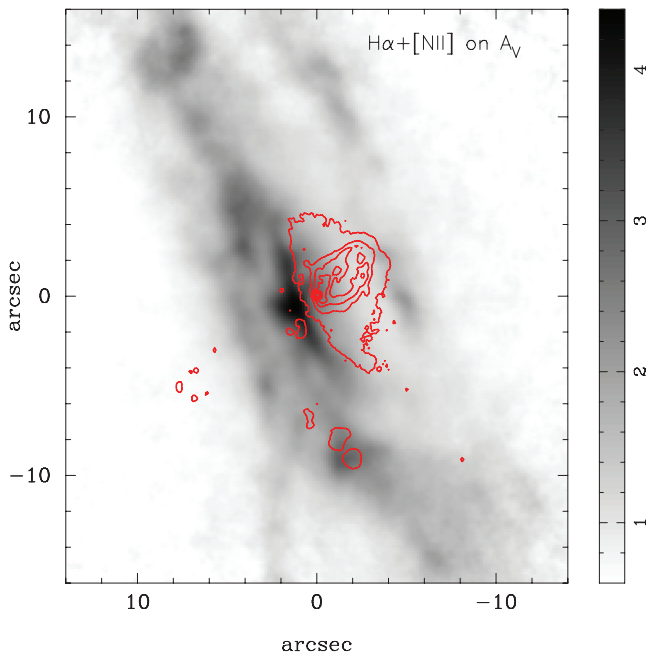
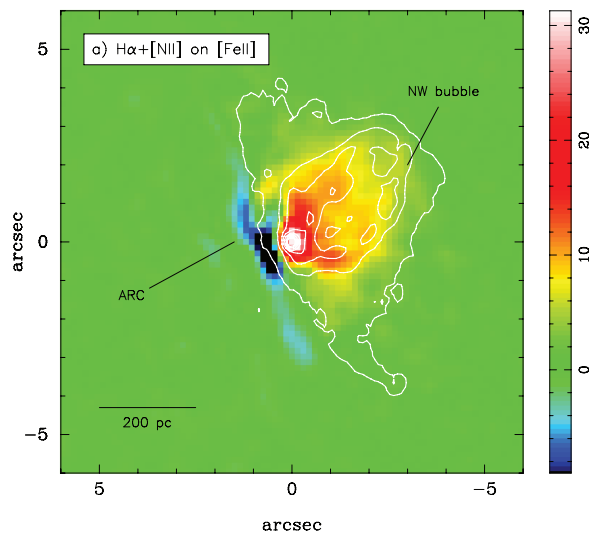


Figure 4. Extinction in the central 40 arcsec of NGC 4438, superposed on *HST* $H\alpha+[NII]$ contour map (Kenney & Yale 2002). The highest extinction corresponds to the region surrounding the nucleus, with a peak of $A_V \sim 4.4$ mag at around 1 arcsec east of the nucleus. Contours are $-0.01, 0.06, 0.27, 0.62, 1.1, 1.73, 2.49, 3.4, 4.44, 5.62, 6.94$ times $2.4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. The x - and y -axes are east and north offsets in arcsec from the nucleus at J2000 RA $12^{\text{h}} 27^{\text{m}} 45.6^{\text{s}}$ and J2000 DEC $+13^{\circ} 00' 32''$ (from the *HST* astrometry).

Tokunaga 2000). 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 $\sim 2 \times 10^{21} \text{ cm}^{-2}$ 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.



3.2 Maps of extended emission

Fig. 5 shows the $[Fe II]$ $1.26 \mu\text{m}$ and H_2 $2.122 \mu\text{m}$ 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 $1\sigma = 1.06 \times 10^{-16} \text{ W m}^{-2} \mu\text{m}^{-1}$, when the slit is aligned with the NW bubble (PA -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 $[Fe II]$ 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 $[Fe II]$ nor H_2 emission.

3.2.1 $[Fe II]$ extended emission

The emission-line map shown in Fig. 5(a) indicates that $[Fe II]$ emission is coincident with *HST* $H\alpha+[NII]$ 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 $H\alpha+[NII]$ 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 $H\alpha+[NII]$ (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 $H\alpha+[NII]$ corresponds to $[NII]$ emission since $H\alpha$ is about two times weaker

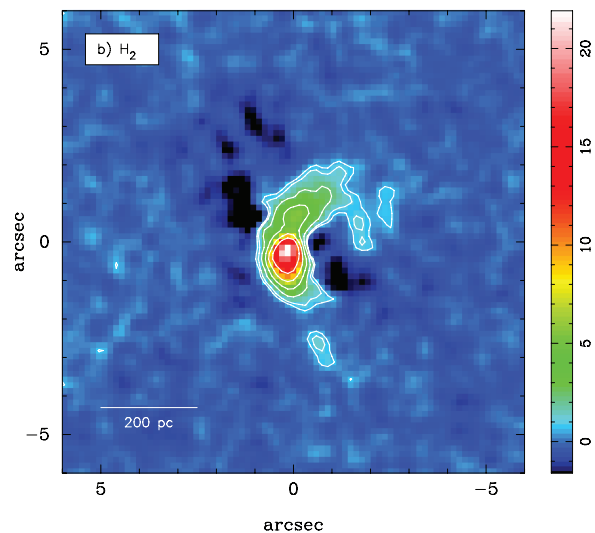


Figure 5. (a) ISAAC $[Fe II]$ continuum subtracted emission-line map of the central 10 arcsec in NGC 4438. Note that there is a negative arc due to $Pa\beta$ contamination in our continuum frame. The colour-scale is exponential and the contours correspond to $H\alpha+[NII]$ emission at 0.12, 0.14, 0.18, 0.27, 0.39 and 0.55 times 32.9 MJy sr^{-1} . (b) Molecular hydrogen (H_2) in the central 10 arcsec of NGC 4438. The colour-scale is exponential and the contours are 0.04, 0.09, 0.18, 0.31, 0.45 and 0.62 times 21.9 MJy sr^{-1} . The x - and y -axes are east and north offsets in arcsec from the nucleus.

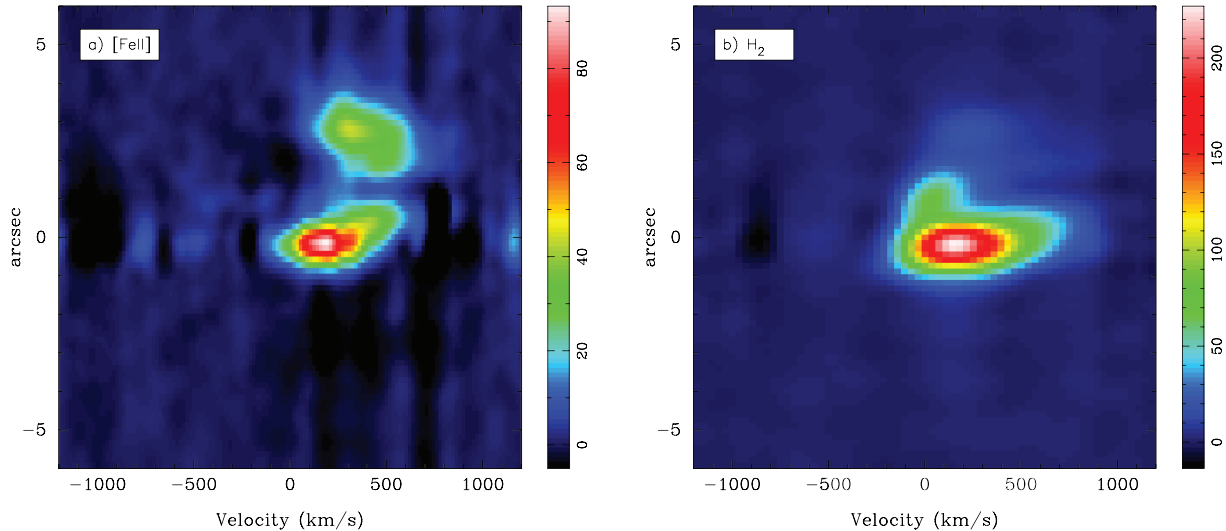


Figure 6. Results of long-slit observations of NGC 4438. Panel (a) shows [Fe II] at 1.257 μm extended emission while panel (b) corresponds to H_2 at 2.122 μm . Spectral PSF subtraction was carried out in order to remove the background and continuum of the galaxy. The slit position for both spectra corresponds to the direction along the major-axis of the NW bubble (position angle is $-57^\circ 65'$), thus giving the velocity gradient across the shell. Intensity is given in units of the rms noise on a pseudo-colour exponential scale. The y-axis is the spatial offset along the slit in arcsec, and the x-axis shows the velocity in the rest frame of the object in km s^{-1} .

than ionized nitrogen emission according to Fig. 1. The bright H II regions, detected in $\text{H}\alpha + [\text{N II}]$ emission 8 arcsec towards the south of the nucleus by Kenney & Yale (2002), do not appear neither in $\text{Pa}\beta$ or [Fe II] emission nor in X-ray emission (Machacek et al. 2004).

In AGN galaxies, the [Fe 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 II] emission is still under debate. Simpson et al. (1996) have argued that photoionization is the dominant excitation mechanism of [Fe 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 II]/ $\text{Pa}\beta$ ratio is a good indicator of the relative contribution of photoionization and shocks, since [Fe 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 $\text{H}\alpha$ and [N II] (see figs 3 and 4 in Kenney & Yale 2002), and therefore also spatially coincident with [Fe II]. This morphological correlation, along with the non-detection of extended $\text{Pa}\beta$ emission in our spectra of the NW bubble, may imply that shock excitation by radio jets contributes to an important fraction of the [Fe II] emission in NGC 4438.

3.2.2 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 H_2 gas from the dissociating AGN radiation field. The 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 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 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 II] and the H_2 emitting gas are distinct. Furthermore, the nuclear [Fe II] line is broader than the H_2 emission. As measured from the nuclear spectra shown in Fig. 3, FWHM of the [Fe II] and $\text{H}_2 \lambda 2.12 \mu\text{m}$ lines are 415 and 270 km s^{-1} , respectively. This implies that the [Fe II] is originating from a kinematically more disturbed gas than the 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 H_2 emitting gas is more restricted to the galactic plane, perpendicular to the radio jets, while the [Fe 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 H_2 excitation is likely to be dominated by X-ray heating from the central AGN.

3.2.3 $\text{Pa}\beta$ extended emission

Fig. 5(a) also shows a negative arc to the east of the nucleus, perpendicular to the NW shell. In this arc $\text{Pa}\beta$ is stronger than the [Fe 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

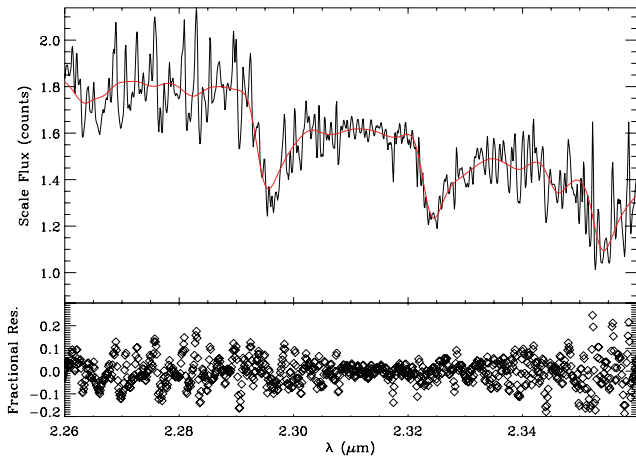


Figure 7. Medium-resolution spectrum centred at $2.310 \mu\text{m}$ with a slits of 0.74 arcsec . The red line represents the best galaxy model fitted by pPXF (see text) as a linear combination of template spectra.

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 $\text{Pa}\beta$ flux density of 0.5 mJy (integrated over the arc-shaped feature), which corresponds to a $\text{Pa}\beta$ luminosity of $3.6 \times 10^{40} \text{ erg s}^{-1}$. 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: $\text{SFR} (M_{\odot} \text{ yr}^{-1}) = 7.9 \times 10^{-42} L(\text{H}\alpha) (\text{erg s}^{-1})$, computed for Case B recombination at $T_e = 10^4 \text{ K}$. Under these conditions the SFR as a function of $\text{Pa}\beta$ luminosity is

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = 1.4 \times 10^{-41} L(\text{Pa}\beta) (\text{erg s}^{-1}), \quad (1)$$

for $j_{\text{H}\alpha}/j_{\text{Pa}\beta} = 17.6$, 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 $1 M_{\odot} \text{ yr}^{-1}$. 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 ($PA = +107^{\circ}5$) 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 rebinned to the spectral resolution of the galaxy spectra (15.47 km s^{-1}

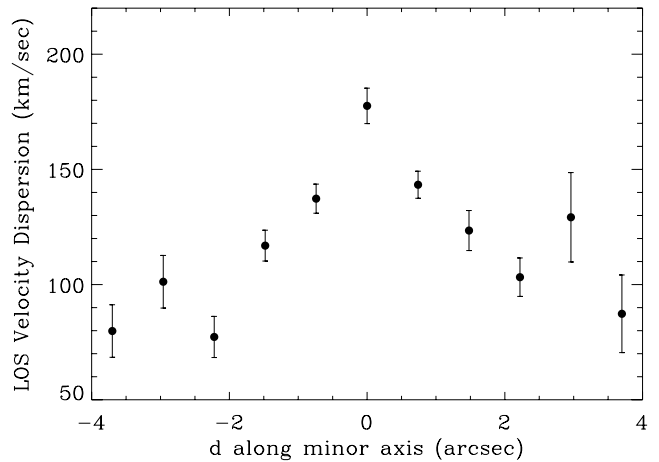


Figure 8. LOS stellar velocity dispersion (σ) as a function of distance along the minor-axis of the galaxy. The LOS velocity dispersion reaches a maximum at the nucleus of the galaxy with $\sigma_{\text{max}} \sim 180 \text{ km s}^{-1}$.

pixel^{-1}). The best-fitting parameters were determined by χ^2 minimization in the pixel space using the penalized pixel fitting method (pPXF) developed by Cappellari & Emsellem (2004), which required a signal-to-noise ratio of at least 30 in order to get reliable stellar kinematics. Errors were estimated by using a Monte Carlo scheme. They were obtained as the standard deviation of the kinematical parameters (V_{los} and σ_{los}) for many realizations ($N = 300$) of the input spectra by adding Gaussian noise to the best model of the galaxy spectrum. The kinematical study of the nature of this putative central mass object requires detailed kinematical model (e.g. Cretton & van den Bosch 1999; Cappellari et al. 2009). Unfortunately, the scarcity of our data does not allow us to perform this kind of analysis.

The results shown in Fig. 8 that NGC 4438 exhibits a strong peak of the LOS velocity dispersion along the minor axis on the centre of the galaxy. The velocity dispersion varies from 100 to 180 km s^{-1} in a region of about 3 arcsec ($\sim 230 \text{ pc}$) in size, which could suggest the presence of a massive central object.

The radius of the sphere of influence of this possible central massive object is just $\sim 0.1 \text{ arcsec}$, which is considerably smaller than our 0.74 arcsec spatial resolution. Therefore, the enhancement observed in the stellar velocity dispersion curve in the inner $\sim 230 \text{ pc}$, where sigma rises from about 100 to 177 km s^{-1} , might be only due to the galaxy bulge potential. However, the sphere of influence is not a hard limit to the influence of a black hole on its host bulge. The influence of the compact object will still be felt at a larger radius but to a lesser extent. Comparing Fig. 8 with the dispersion profiles of other AGNs such as NGC 2549, whose sphere of influence is also $\sim 0.1 \text{ arcsec}$ (see fig. 4 in Krajnovic et al. 2009), NGC 4438's velocity dispersion seems to be even steeper in the central couple of arcsec. Therefore, we cannot rule out the presence of a supermassive black hole as responsible for the central enhancement in the velocity dispersion profile of NGC 4438.

4 SURFACE BRIGHTNESS MODELLING OF NGC 4438

4.1 Model description: general considerations

Does the nucleus seen in our broad-band images correspond to a cuspy surface-brightness profile or is it a point source? Our

¹ See NIR resources at: <http://www.gemini.edu/sciops/instruments/>

Table 3. Best NGC 4438 galaxy structural parameters.

Filter (1)	Δ (2)	q (3)	c (4)	α (5)	n (6)	R_e (7)	I_e (8)	R_h (9)	I_0 (10)	n' (11)	R'_e (12)	I'_e (13)	L_{tot} (14)	$\log \mathcal{M}_{\text{bh}}$ (15)	$\log \mathcal{M}_{\text{bh}}(n)$ (16)
bulge + disc + Sérsic nucleus															
<i>J</i>	30	0.57	1.10	68.3	1.65	3.88	71.76	13.46	42.65	1.75	~ 0	572.63	27.7	7.19	6.90 ± 0.45
<i>H</i>	30	0.57	1.14	68.4	1.47	3.53	94.76	12.77	57.08	1.93	~ 0	502.12	21.8	6.97	6.68 ± 0.45
<i>Ks</i>	30	0.57	1.13	68.7	1.52	3.49	73.39	12.86	41.34	1.71	~ 0	570.92	13.0	6.66	6.75 ± 0.45
<i>B</i>	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 Sérsic structural parameters for the bulge, R_e and R_h are in units of arcsec. (11)–(13) are the Sérsic 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 \mathcal{M}_{bh} –luminosity density relation (Marconi & Hunt 2003). (16) Black hole masses obtained from the $\mathcal{M}_{\text{bh}}-n$ 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 $r^{1/n}$ Sérsic 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 Sérsic 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 (30×30 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 Sérsic 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

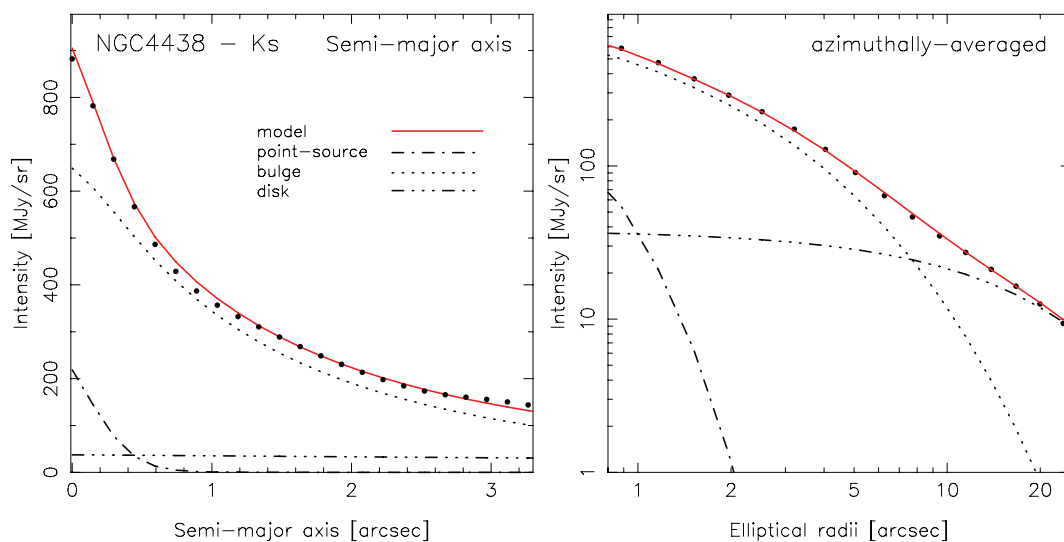


Figure 9. Results of the two-dimensional decomposition of NGC 4438 (see text). Left-hand panel: semimajor axis cut to the central 3 arcsec. The dashed line is the dereddened galaxy profile. Right-hand panel: Surface brightness azimuthally averaged over a radial elliptical annulus (points) of width $\Delta r \sim 0.2$ arcsec, with r defined by equation (B1) (axes are in logarithm scale).

Table 4. NIR nuclear source photometry.

Filter	Central λ (μm)	F_λ (mJy)	M_λ (mag)	L_λ ($10^{41} \text{ erg s}^{-1}$)
<i>J</i>	1.25	10	-17.96	7.35
<i>H</i>	1.65	12	-18.66	6.67
<i>K_s</i>	2.16	8	-18.67	3.40

^aThe specific luminosity was computed as $L_\nu = 4\pi D^2 \nu F_\nu$, at a distance $D = 16 \text{ Mpc}$.

isophote twists or ellipticity. For this reason, the right-hand panel shows the surface brightness azimuthally averaged along a radial elliptical annulus;² 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.³ 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 $R_e = 0.2 \text{ arcsec}$, 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 $2 \times 2 \text{ arcsec}^2$ 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 $F_0 \delta(x_{\text{cen}}, y_{\text{cen}})$ convolved with a Gaussian of $\text{FWHM} = 0.4 \text{ arcsec}$. The free parameters were the $(l + 1) \times (k + 1)$ Legendre coefficients, the centroid of the compact-source $(x_{\text{cen}}, y_{\text{cen}})$, 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 $\text{FWHM} = 0.4 \text{ arcsec}$, 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 $R_e = 0.2 \text{ arcsec}$ since $\text{FWHM} \sim 2R_e$.

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 $M_B \sim -12.24 \text{ mag}$.

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 $\text{H}\alpha$ emission (Ho et al. 1997; Kenney & Yale 2002). We constructed the NGC 4438 SED of the non-stellar component using data from radio ($\nu = 4.86 \times 10^9 \text{ Hz}$) to hard X-rays ($\nu = 1.7 \times 10^{18} \text{ Hz}$).

The NIR data ($\log(\nu/\text{Hz}) \sim 14$) 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 [$\log(\nu/\text{Hz}) \sim 13.4$] photometry of the nuclear source was extracted over a 4.5 arcsec circular aperture in the TIMM2 NB 11.9 μm image (see Fig. 10). The result was a mid-IR flux density of $0.20 \pm 0.04 \text{ Jy}$. 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 [$\log(\nu/\text{Hz}) = 17.6$] and hard [$\log(\nu/\text{Hz}) = 18.2$] X-ray counterparts were obtained from *Chandra* data reported in table 4 of Machacek et al. (2004), without any absorption correction. The radio continuum [$\log(\nu/\text{Hz}) = 9.3$] data were obtained from Hummel & Saikia (1991). This measurement was computed by integrating the extended emission over a rectangle of sides $2 \times 5 \text{ arcsec}^2$. It gives $1.5 \pm 0.3 \text{ mJy}$. This value corresponds to an upper limit since

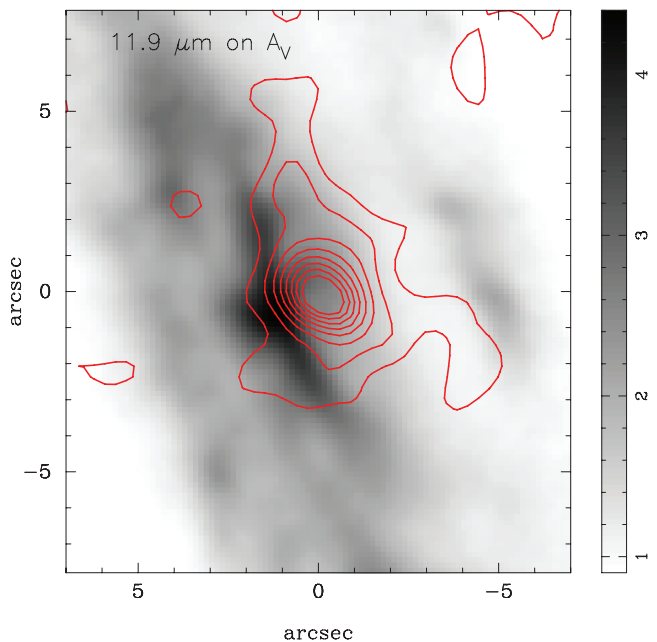


Figure 10. ISAAC A_V greyscale map superposed on TIMM2 NB 11.9 μm emission map (contours). Contours are $-0.27, 0.24, 0.40, 0.52, 0.61, 0.69, 0.77, 0.83$ and 0.89 times 385 MJy sr^{-1} . The x - and y -axes are east and north offsets in arcsec from the nucleus. The TIMM2 astrometry is uncertain to $\sim 5 \text{ arcsec}$.

² With the same nomenclature of the left-hand panel, in logarithmic scale.

³ We did not model the *R*- and *I*-band images because the few pixels covering the nucleus were severely saturated.

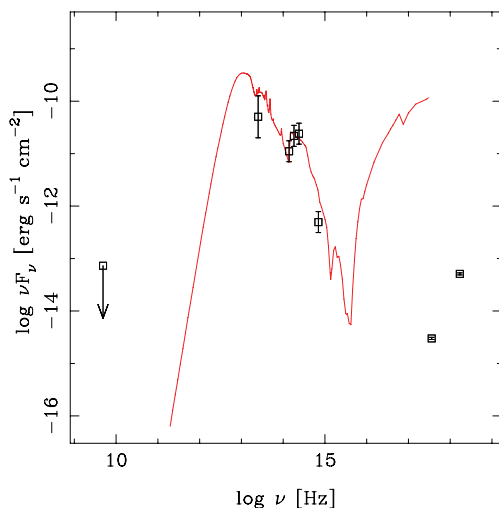


Figure 11. Spectral energy distribution of distinct nuclear source (AGN) in NGC 4438. The solid line is a theoretical SED based on radiative transfer calculations with a central AGN as the heating source. See text for information about data and models. The weak high-energy emission from the nucleus of 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 $L(\nu/\text{Hz}) \propto (\nu/\text{Hz})^{-0.7}$ 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 $L_{\text{Edd}} \sim 10^{45} \text{ erg s}^{-1}$ 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 H α (Cardelli et al. 1989), implying an extinction-corrected SFR of $0.08 M_{\odot} \text{ yr}^{-1}$ for the nucleus. On the other hand, the SFRs inferred from the extinction-corrected Pa β emission is $1 M_{\odot} \text{ yr}^{-1}$ 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 II 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 $\sim 350 \text{ km s}^{-1}$ 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 $\sim 500 \text{ km s}^{-1}$ at 2 arcsec to $\sim 350 \text{ km s}^{-1}$ 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 α 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 ~ 3 , yielding an injected kinetic energy into the halo of the galaxy of $> 10^{54} \text{ erg}$. 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 β 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 $R_{\text{BH}} \sim 0.1$ 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 σ , 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 $\sigma = 142 \pm 8 \text{ km s}^{-1}$ 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 $\mathcal{M}_{\text{bh}}-\sigma$ relation using this value yields a mass for the central black hole of $\log(\mathcal{M}_{\text{bh}}/M_{\odot}) = 7.5 \pm 1.7$.

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 $\mathcal{M}_{\text{bh}}-n$ 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 $\mathcal{M}_{\text{bh}}-n$ 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 $\log(\mathcal{M}_{\text{bh}}/M_{\odot}) = 6.70 \pm 0.45$ 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 \mathcal{M}_{bh} is the NIR luminosity (Marconi & Hunt 2003), which provides a $\mathcal{M}_{\text{bh}}-\text{bulge}$ 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 II] emission coincident with the NW bubble seen in radio continuum, X-rays and optical emission. The morphological correlation between [Fe II] and previous radio observations, along with the absence of Pa β 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 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 α , which could be up to $0.08 M_{\odot} \text{ yr}^{-1}$, 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, $> 10^{54} \text{ erg}$, along with the weak star formation suggests that an AGN is more likely to power the outflow.

(iii) The H₂ 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 H₂ is kinematically distinct from the gas radiating [Fe II] emission. Moreover, the nuclear [Fe II] line (FWHM $\sim 415 \text{ km s}^{-1}$) is broader

than the nuclear H₂ emission (FWHM $\sim 270 \text{ km s}^{-1}$), implying that the [Fe II] gas is kinematically more disturbed than the H₂ gas. Furthermore, the molecular gas seems to be more restricted to the galactic plane, while [Fe 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 H₂.

(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 $n \sim 1.7$ and $R_e \sim 3 \text{ arcsec}$, an exponential disc with $R_h \sim 13 \text{ arcsec}$, and a compact nuclear source, resolved in *HST* with $R_e \sim 0.2 \text{ arcsec}$. 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 $10^7 M_{\odot}$ 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 $177 \pm 8 \text{ km s}^{-1}$.

(viii) A black hole mass of $\log(\mathcal{M}_{\text{bh}}/M_{\odot}) \sim 7$ 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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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 rays 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 ~ 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 covariance 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 (~ 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 $\sigma_r^2 = \sigma_{\text{rms}}^2 + \sigma_{\text{calib}}^2$. 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

difference between 2MASS photometry and our photometry of the standard stars named above, and differences of 12, 14 and 10 per cent for JHK_s , respectively for NGC 4438. This could be caused by an overestimation of the sky level in our reduction procedure.

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,

$$r = (|x|^{2/c} + |y/q|^{2/c})^{c/2}, \quad (\text{B1})$$

where q is related to the ellipticity by $e = 1 - q$. 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 α , 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 α is defined with respect to the image pixel coordinate system, increasing counterclockwise.

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

$$I_b(r) = I_e \exp \left\{ -b_n \left[\left(\frac{r}{R_e} \right)^{1/n} - 1 \right] \right\}, \quad (\text{B2})$$

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 Γ and γ are the complete and incomplete gamma functions, respectively. Analytical expressions which approximate the value of 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 Sérsic profile, we integrated over a generalised elliptical radius r . It gives

$$F_v(r) = \pi I_e e^{b_n} R_e^2 \frac{2n}{b_n^{2n}} \gamma(2n, x) \mathcal{I}(q, c), \quad (\text{B3})$$

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

$$\mathcal{I}(q, c) = \frac{2qc}{\pi} \int_0^{\pi/2} (\sin \phi \cos \phi)^{c-1} d\phi. \quad (\text{B4})$$

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 $I_d(r) = I_0 \exp(-r/R_h)$, where the parameter R_h 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

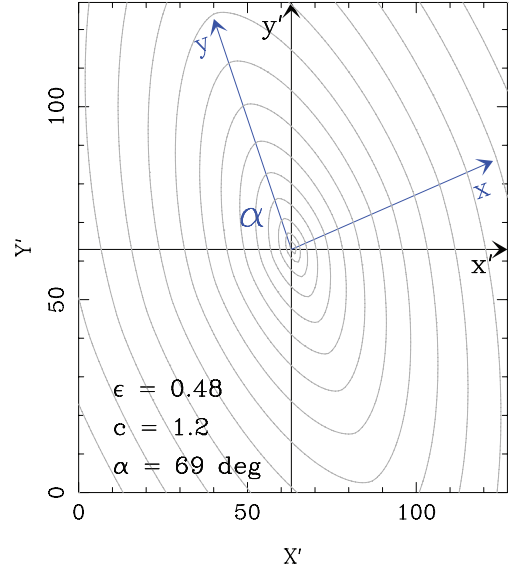


Figure B1. Best-fitting isophotes model to NGC 4438 with constant ellipticity $\epsilon = 0.48$, angle $\alpha = 69^\circ$ and $c = 1.2$. This figure also shows the convention used for the pixel coordinates X' , X , and the angle α .

(for a point source) or a Sérsic component (for resolved sources). Finally, the model takes the form:

$$I(r) = [I_{\text{nuc}}(r) + I_b(r) + I_d(r)] \otimes \text{PSF}, \quad (\text{B5})$$

where $I(r)$ is the surface brightness at a radius r (defined in equation B1), I_{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_{cen} , y_{cen}), those related to the elliptical geometry: α , q , i and c ; the Sérsic profile power-law index n , the effective radius R_e , the effective intensity I_e ; the exponential disc scale length R_h and central luminosity I_0 ; the nuclear source parameters: n' , R'_e and I'_e (Sérsic case) or the central flux density (delta function case).

We found the best-fitting solution by performing a χ^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 χ^2 .
- (5) Iterate from step 2 until convergence is reached.
- (6) Generate output images: residual image, original galaxy image and model.

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