

# The complex, dusty narrow-line region of NGC 4388: gas–jet interactions, outflows and extinction revealed by near-IR spectroscopy

A. Rodríguez-Ardila,<sup>1\*</sup> R. E. Mason,<sup>2</sup> L. Martins,<sup>3</sup> C. Ramos Almeida,<sup>4,5</sup>  
R. A. Riffel,<sup>6</sup> R. Riffel,<sup>7</sup> P. Lira,<sup>8</sup> O. González Martín,<sup>9</sup> N. Z. Dametto,<sup>7</sup>  
H. Flohic,<sup>10</sup> L. C. Ho,<sup>11,12</sup> D. Ruschel-Dutra,<sup>7</sup> K. Thanjavur,<sup>13</sup>  
L. Colina,<sup>14</sup> R. M. McDermid,<sup>15,16</sup> E. Perlman<sup>16</sup> and C. Winge<sup>2</sup>

<sup>1</sup>Laboratório Nacional de Astrofísica/MCTI, Rua dos Estados Unidos, 154, Bairro das Nações, 37504-364 Itajubá, MG, Brazil

<sup>2</sup>Gemini Observatory, Hawaii, Northern Operations Center, 670 North A'ohoku Place, Hilo, HI 96720, USA

<sup>3</sup>NAT-Universidade Cruzeiro do Sul, Rua Galvão Bueno, 868, 01506-000 São Paulo, SP, Brazil

<sup>4</sup>Instituto de Astrofísica de Canarias, Calle Vía Láctea, s/n, E-38205 La Laguna, Tenerife, Spain

<sup>5</sup>Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain

<sup>6</sup>Departamento de Física/CCNE, Universidade Federal de Santa Maria, 97105-900 Santa Maria, RS, Brazil

<sup>7</sup>Instituto de Física, Universidade Federal do Rio Grande do Sul, CP 15051, Porto Alegre 91501-970, RS, Brazil

<sup>8</sup>Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

<sup>9</sup>Instituto de Radioastronomía y Astrofísica (IRAF-UNAM), 3-72 (Xangari), 8701 Morelia, Mexico

<sup>10</sup>Department of Physics, University of the Pacific, 3601 Pacific Avenue, Stockton, CA 95211, USA

<sup>11</sup>Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China

<sup>12</sup>Department of Astronomy, Peking University, Beijing 100871, China

<sup>13</sup>Department of Physics & Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada

<sup>14</sup>Centro de Astrobiología (CAB, CSIC-INTA), Carretera de Ajalvir, E-28850 Torrejón de Ardoz, Madrid, Spain

<sup>15</sup>Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia

<sup>16</sup>Department of Physics & Space Sciences, Florida Institute of Technology, 150 West University Boulevard, Melbourne, FL 32901, USA

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## ABSTRACT

We present Gemini/GNIRS (Gemini Near-Infrared Spectrograph) spectroscopy of the Seyfert 2 galaxy NGC 4388, with simultaneous coverage from 0.85 to 2.5  $\mu\text{m}$ . Several spatially extended emission lines are detected for the first time, both in the obscured and unobscured portion of the optical narrow-line region (NLR), allowing us to assess the combined effects of the central continuum source, outflowing gas and shocks generated by the radio jet on the central 280 pc gas. The H I and [Fe II] lines allow us to map the extinction affecting the NLR. We found that the nuclear region is heavily obscured, with  $E(B - V) \sim 1.9$  mag. To the NE of the nucleus and up to  $\sim 150$  pc, the extinction remains large,  $\sim 1$  mag or larger, consistent with the system of dust lanes seen in optical imaging. We derived position–velocity diagrams for the most prominent lines as well as for the stellar component. Only the molecular gas and the stellar component display a well-organized pattern consistent with disc rotation. Other emission lines are kinematically perturbed or show little evidence of rotation. Extended high-ionization emission of sulphur, silicon and calcium is observed to distances of at least 200 pc both NE and SW of the nucleus. We compared flux ratios between these lines with photoionization models and conclude that radiation from the central source alone cannot explain the observed high-ionization spectrum. Shocks between the radio jet and the ambient gas are very likely an additional source of excitation. We conclude that NGC 4388 is a prime laboratory to study the interplay between all these mechanisms.

**Key words:** galaxies: individual: NGC 4388 – galaxies: jets – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies.

\* E-mail: [aardila@lna.br](mailto:aardila@lna.br)

## 1 INTRODUCTION

Active galactic nuclei (AGNs) commonly have outflows and jets, and these structures/phenomena may strongly influence the surroundings of the AGN. While direct jet–gas interactions affect the velocity field of the local medium, they also produce fast, auto-ionizing shocks which can significantly influence (or even dominate) the observed emission-line strengths and kinematics. In nearby AGNs, the warm ( $T \sim 10^4$  K), ionized gas in the narrow-line region (NLR) can be resolved on scales of a few tens of parsecs in the optical and near-infrared (NIR). They are therefore useful laboratories for determining the extent and kinematics of the various species in the gas, and the role of shocks in producing the integrated emission-line spectrum (Emonts et al. 2005; Rodríguez-Ardila et al. 2006; Morganti et al. 2013).

Because extinction by dust is lower by a factor of  $\sim 10$  relative to the optical, NIR spectroscopy allows us to probe depths unreachable at shorter wavelengths. Seyfert 2 galaxies are the preferred targets as the line of sight to the nucleus is blocked by the intervening dust and molecular material, allowing the study of the environment of the AGN without the effect of dilution caused by the bright central source.

In this context, NGC 4388, a highly inclined ( $i \sim 78^\circ$ ; Veilleux, Bland-Hawthorn & Cecil 1999) Seyfert 2 galaxy in the Virgo cluster (Helou, Salpeter & Krumm 1981), is a prime target for studying possible feedback effects of the supermassive black hole (SMBH) on the distribution and kinematics of ionized gas and stars. To start with, it was one of the first galaxies in which a conically shaped NLR was detected (Pogge 1988; Yoshida et al. 2002). WFPC2/*HST* (Wide Field Planetary Camera 2/*Hubble Space Telescope*) observations reported by Schmitt et al. (2003) in the [O III] filter confirmed the V-shaped NLR with opening angle of  $90^\circ$  towards the south, extended over 560 pc in this direction. In the perpendicular direction, [O III] was detected over 720 pc. Most of the [O III] emission comes from regions south of the nucleus, except for some emission corresponding to the counter-cone, which is obscured by the host galaxy, at the NE side of the nucleus. Galactic-scale outflows as well as a rich complex of highly ionized gas which extends  $\sim 4$  kpc above the disc were detected by Veilleux et al. (1999). Matt et al. (1994) detected soft X-ray emission extending over 4.5 kpc in observations with *ROSAT*. Later, Iwasawa et al. (2003) and Bianchi, Guainazzi & Chiaberge (2006) using *Chandra* found that the soft X-ray emission is coincident in extent and overall morphology with [O III]  $\lambda 5007$  Å. In the radio, Stone, Wilson & Ward (1988) and Hummel & Saikia (1991) found that NGC 4388 is double-peaked with a primary peak on the nucleus and a secondary peak 230 pc south-west of it. They also report a plume of radio plasma to the north of the optical nucleus. The good overall match between optical emission line and radio morphology reported by Falcke, Wilson & Simpson (1998) led them to suggest that NGC 4388 is an example of an interaction between a radio jet and ambient gas.

An additional property which makes NGC 4388 interesting is the presence of water maser emission from a circumnuclear disc, allowing accurate measurement of the mass of its SMBH. Kuo et al. (2011), using very long baseline interferometry, studied the kinematics of the water maser emission and derived a BH mass of  $8.5 \pm 0.2 \times 10^6 M_\odot$ . Moreover, Greene et al. (2013) found a stellar nuclear disc with position angle (PA) of  $75^\circ$ , radius of  $\sim 200$  pc and a 100 pc-scale jet oriented at a PA of  $24^\circ$ .

In the NIR, NGC 4388 has not been studied very extensively, with most spectroscopic studies reported in the *K* and *J* bands only (Winge et al. 2000; Knop et al. 2001; Lutz et al. 2002;

Imanishi & Alonso-Herrero 2004; van der Laan et al. 2013; Greene et al. 2014). They all indicate that NGC 4388 is a complicated system with much spatial structure at all wavelengths. Very recently, Greene et al. (2014) found, by means of *K*-band integral field unit (IFU) data, a drop in the stellar velocity dispersion in the inner  $\sim 100$  pc, interpreted as the signature of a dynamically cold central component. They also report [Si VI]  $1.963 \mu\text{m}$  and Br $\gamma$  oriented at PA  $\sim 30^\circ$ , aligned with the jet on similar scales, and also with the [O III] emission which traces the NLR.

Because of the mounting evidence of jet–gas interactions and rich circumnuclear structures/environment in NGC 4388, we are interested in studying the inner 500 pc of this source to more closely examine the physical conditions of the atomic, molecular and ionized gas. Our aim is to carry out, for the first time, a simultaneous analysis of the spectral region  $0.84\text{--}2.5 \mu\text{m}$ . It includes the wavelength intervals where the brightest NIR lines in AGNs are located (i.e. [S III]  $0.953 \mu\text{m}$ , He I  $1.083 \mu\text{m}$ , [Si VII]  $2.483 \mu\text{m}$ ), and these lines have not yet been observed in NGC 4388. We perform detailed 1D mapping along PA =  $64^\circ$  of the most relevant NIR spectroscopic properties, searching for features of the morphology and gas kinematics which will help us to understand the origin and nature of the nuclear/circumnuclear gas, and its role within the AGN and outflows already detected in this source.

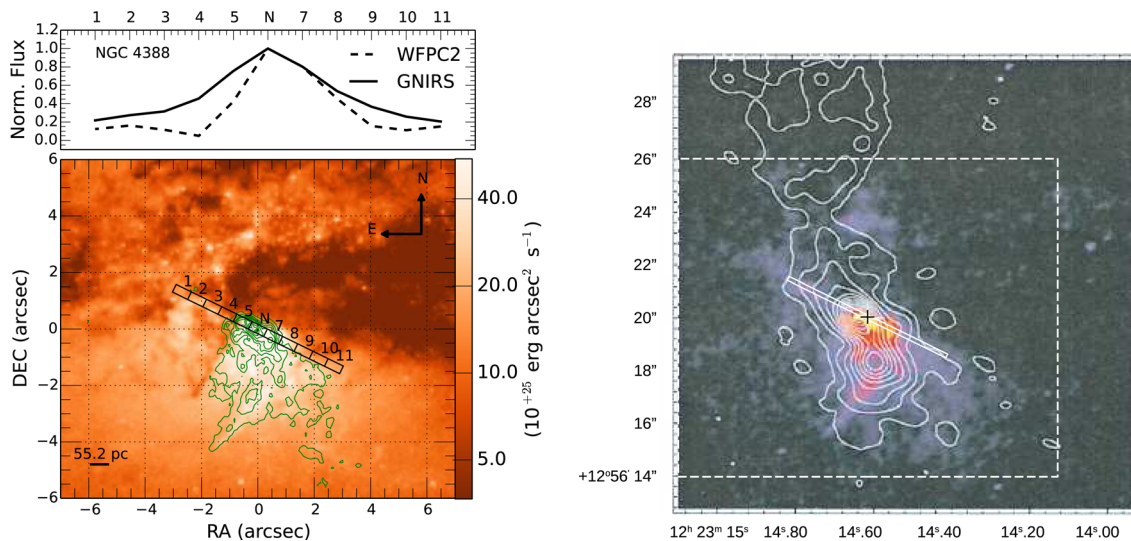
This paper is structured as follows. In Section 2, we describe the observations and data reduction. In Section 3, we describe the most important NIR features detected in the spectra, and analyse the main spectral (line and continuum) properties including the extinction affecting the gas and the main excitation mechanisms which produce the observed lines. Section 4 discusses the kinematics of the neutral, low-, medium- and high-ionization gas as well as the kinematics of the stellar component. Section 5 deals with the main ionization mechanisms of the high-excitation gas. Section 6 contains the main conclusions found from our work. Throughout this paper, we adopt the Tully–Fisher distance to NGC 4388 of 19 Mpc (Kuo et al. 2011), which translates into a spatial scale of  $92 \text{ pc arcsec}^{-1}$ . Emission lines with wavelengths shortwards of  $1 \mu\text{m}$  will be quoted in angstroms (Å) while those longwards of that value will be quoted in microns ( $\mu\text{m}$ ).

## 2 OBSERVATIONS AND DATA REDUCTION

NGC 4388 was observed as part of a set of NIR spectroscopic observations of galaxies from the Palomar nearby galaxy survey (Ho, Filippenko & Sargent 1997; Mason et al. 2015). The spectra were obtained using the cross-dispersed mode of the Gemini Near-Infrared Spectrograph (GNIRS) on the Gemini North 8.1 m telescope.<sup>1</sup> This configuration provides a continuous spectral coverage from  $\sim 8400$  Å to  $2.48 \mu\text{m}$  at a spectral resolution of  $\sim 1200$  with a spatial scale of  $0.15 \text{ arcsec pixel}^{-1}$ . The  $0.3 \text{ arcsec} \times 7 \text{ arcsec}$  slit was set at a PA =  $64^\circ$  east of north and centred on the peak of the  $1.6 \mu\text{m}$  emission. The seeing during the galaxy observation was  $0.6 \text{ arcsec}$  as measured from the telluric A1V standard HIP 58616, observed right before the galaxy at a similar airmass. The left-hand panel of Fig. 1 shows the slit position overlaid on the WFPC/*HST* F606W ( $5935 \text{ Å}$ ) image of NGC 4388. The contours correspond to WFPC/*HST* observations of [O III]  $\lambda 5007$ , described in Falcke et al. (1998).

The observations used an object–sky–object pattern, with the sky position 50 arcsec away from the galaxy nucleus, free of

<sup>1</sup> Programme ID: GN-2013A-Q-16



**Figure 1.** Left: continuum WFPC2/*HST* in the  $F606W$  filter overlaid on  $[O\text{ III}]\lambda 5007$  contours (described in Falcke et al. 1998). The GNIRS slit is positioned at an angle of  $PA=64^\circ$  and illustrates approximately the region covered by the NIR spectra. ‘N’ marks the position of the nuclear aperture while the numbers 1 to 5 and 7 to 11 denote the off-nuclear extractions. The two curves on top show the light profile along the spatial direction of the slit for the GNIRS spectrum (black solid line) and in the  $[O\text{ III}]\lambda 5007$  image at the same PA as the slit (dashed line). North is up and east is to the left. The spatial scale is indicated by the bar at the bottom-left corner and represents the size of the aperture window used in extracting the spectra. Right:  $H\alpha$  image from WFPC2/*HST* overlaid on radio contours as originally published by Falcke et al. (1998). The thick white box represents the GNIRS slit while the dashed square marks approximately the field covered by the image to the left. The black cross is the position of the optical nucleus.

extended emission or background stars. Four individual on-source integrations of 240 s each were carried out.

The spectral reduction, extraction, and wavelength and flux calibration procedures were performed using version 1.9 of the ‘XDGNIRS’ code detailed in Mason et al. (2015). Briefly, the processing consists of removing cosmic ray-like features, dividing by a flat-field, subtracting sky emission and rectifying the tilted, curved spectra. Wavelength calibration is achieved using argon arc spectra, and then a spectrum of each order is extracted, divided by a standard star to cancel telluric absorption lines, and roughly flux-calibrated using the telluric standard star spectrum. The pipeline merges the different spectral orders for each extraction window into a single 1D spectrum from 0.84 to 2.48  $\mu\text{m}$ . In all cases, the agreement in flux between the overlapping regions of two consecutive orders was very good, and scaling factors of  $<3$  per cent were necessary.

The brightest emission lines clearly extend all along the slit, so 10 off-nuclear extractions were made in the spatial direction, as shown in Fig. 1. ‘N’ represents the region where the nuclear spectrum was extracted, centred at the peak of the continuum emission. The labels 1 to 11 mark the different extractions, with 1 to 5 to the NE and 7 to 11 to the SW. The aperture size of the extraction window used in all cases was 0.6 arcsec, similar to the seeing measured from the telluric standard.

Fig. 2 shows the nuclear spectrum in the galaxy frame with the most conspicuous emission lines identified in the laboratory frame. Fig. 3 displays all extractions made along the spatial direction, also in the galaxy frame. A Galactic extinction of  $A_V$  of 0.09 from Schlegel, Finkbeiner & Davis (1998) was found for this source. Because it is negligible, we have not corrected for this effect.

### 3 THE NIR SPECTRUM OF NGC 4388

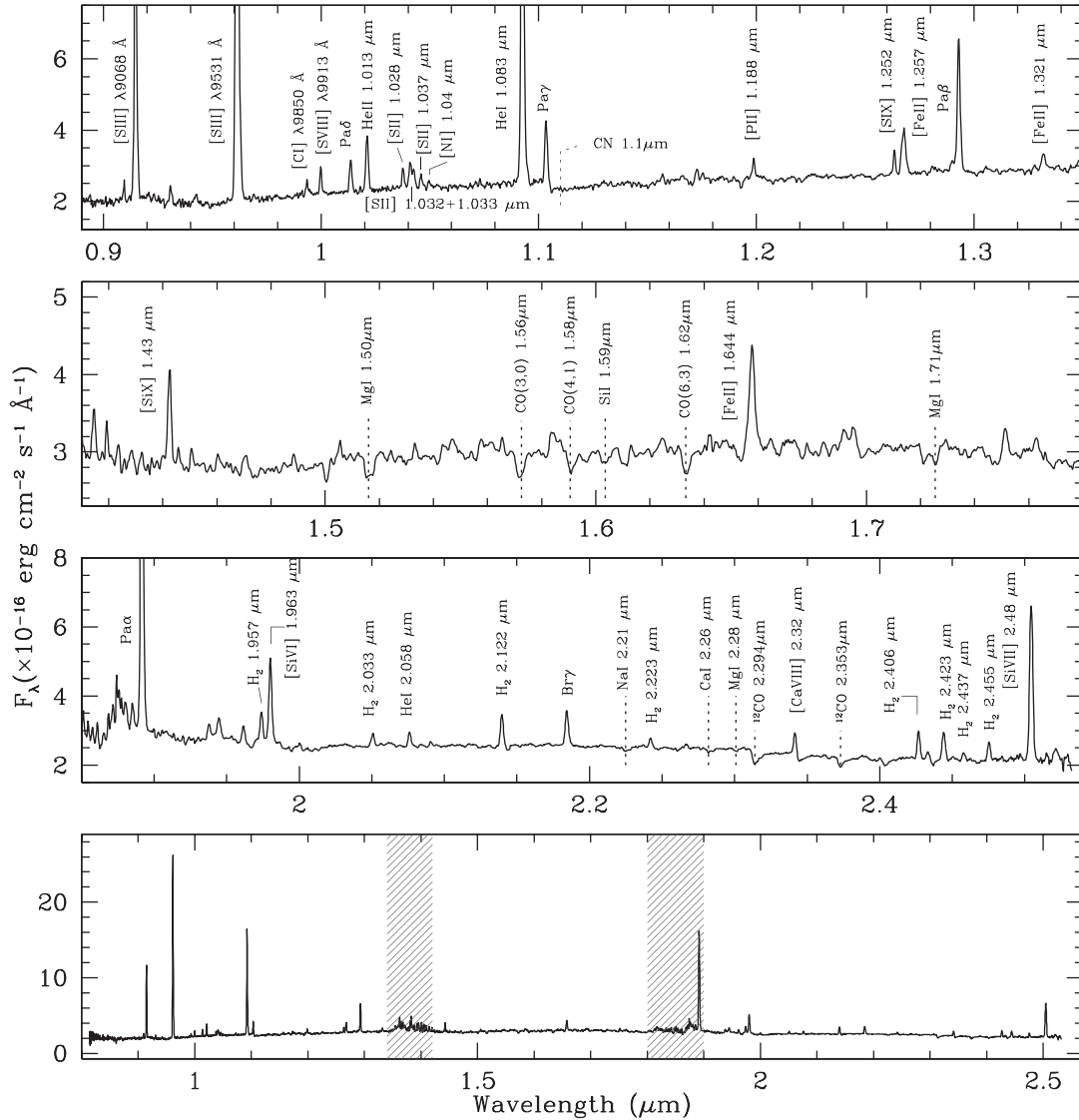
Figs 2 and 3 reveal that NGC 4388 displays an outstanding emission-line spectrum with prominent lines of  $[S\text{ III}]\lambda\lambda 9068, 9531\text{ \AA}$ ,  $\text{He I } 1.083\text{ }\mu\text{m}$ ,  $[\text{Fe II}] 1.257\text{ }\mu\text{m}$ ,  $\text{Pa}\beta$ ,  $\text{H}_2 2.122\text{ }\mu\text{m}$ ,  $[\text{Si VI}] 1.963\text{ }\mu\text{m}$

and  $[\text{Si VII}] 2.48\text{ }\mu\text{m}$ . These lines all extend from the nucleus to the NE and SW ends of the slit. Extended emission of  $[\text{Fe II}]$ ,  $\text{Pa}\beta$ ,  $\text{H}_2 2.122\text{ }\mu\text{m}$  and  $[\text{Si VI}]$  have previously been reported for this AGN (Knop et al. 2001; van der Laan et al. 2013; Greene et al. 2014). Our data, however, reveal that not only are those lines spatially resolved but also  $[S\text{ III}]$ ,  $[\text{C I}]$ ,  $\text{He I}$ ,  $[\text{S IX}]$  and  $[\text{Si VII}]$ , which are detected at distances of up to 280 pc NE and SW of the nucleus.

The presence of high-ionization lines in the nuclear and off-nuclear spectra of NGC 4388 is also evident from Figs 2 and 3.  $[\text{Si VII}] 2.48\text{ }\mu\text{m}$ , a coronal line (CL) with ionization potential (IP) = 205 eV, is the second brightest forbidden line after  $[S\text{ III}] 0.953\text{ }\mu\text{m}$ . In addition to  $[\text{Si VII}]$ , we also report here first detections of  $[S\text{ VIII}] 0.991\text{ }\mu\text{m}$ ,  $[\text{Si X}] 1.43\text{ }\mu\text{m}$  and  $[\text{Al IX}] 2.048\text{ }\mu\text{m}$ . The latter two are rather compact, with no evidence of extended emission.  $[S\text{ IX}] 1.252\text{ }\mu\text{m}$  and  $[\text{Ca VIII}] 2.32\text{ }\mu\text{m}$  are also detected in our data in the nuclear and off-nuclear apertures. These lines were previously reported by Knop et al. (2001) and Greene et al. (2014), respectively.

In addition to the emission lines, the continuum emission of NGC 4388 displays stellar absorption features of CO and CaT in the extreme red and blue portions of the NIR spectra, respectively. Moreover, absorption lines of  $\text{Mg I}$ , CO and  $\text{Si I}$  are also evident in the  $H$  band. The CN band at 1.1  $\mu\text{m}$  is prominent in the nuclear and circumnuclear apertures, indicating the presence of red giant and/or asymptotic giant branch stars (Riffel et al. 2015a).

Fig. 4 displays the light distribution along the spatial direction of the brightest emission lines detected in this object. For comparison, the light profile of the continuum at different wavelengths is also shown. It can be seen that the NLR of NGC 4388 has a complex, irregular structure. For most lines, the brightest emission coincides with the peak of the continuum light (and we identify this location as the active nucleus). The exception is the  $[S\text{ III}]\lambda 9531$  line, which reaches its maximum  $\sim 50$  pc SW of the continuum peak. In fact, many of the lines show secondary peaks  $\sim 50$  pc SW of the nucleus. Such peaks are particularly prominent in  $\text{He I}$ ,  $[\text{Si VI}]$  and  $[\text{Si VII}]$ . A third peak is observed at  $\sim 150$  pc SW from the nucleus, most



**Figure 2.** Nuclear spectrum of NGC 4388 in the galaxy frame for the  $Y + J$  bands (upper panel),  $H$  band (second panel) and  $K$  band (third panel), with the most conspicuous emission lines identified. The wavelengths of the lines are in the laboratory frame. Absorption lines/bands are marked by dotted lines. The last panel shows the overall continuum shape and brightest emission features detected in this source in the wavelength interval covered by GNIRS. The shaded regions correspond to regions of low atmospheric transmission.

noticeable in  $\text{Pa}\beta$ ,  $[\text{Fe II}]$  and  $[\text{Si VII}]$  but also detected in other lines. A fourth peak of emission at  $\sim 150$  pc NE of the nucleus is detected, quite prominent in  $[\text{S III}]$  and also observed in  $\text{He I}$ ,  $\text{H I}$ ,  $[\text{Fe II}]$ ,  $[\text{Si VI}]$  and  $[\text{Si VII}]$ .

The asymmetry of the line distributions, with excess emission towards the SW compared with the NE, is most pronounced at shorter wavelengths. This reflects the dusty nature of NGC 4388, whose inner few hundred parsecs from the centre to the NE are highly obscured at optical wavelengths. Strong dust lanes crossing the nuclear and circumnuclear region are evident in the WFPC/*HST* images of Schmitt et al. (2003). The fact that the NIR region is significantly less affected by dust allows us to map this hidden region in a variety of emission lines, something which has not been possible using optical spectroscopy.

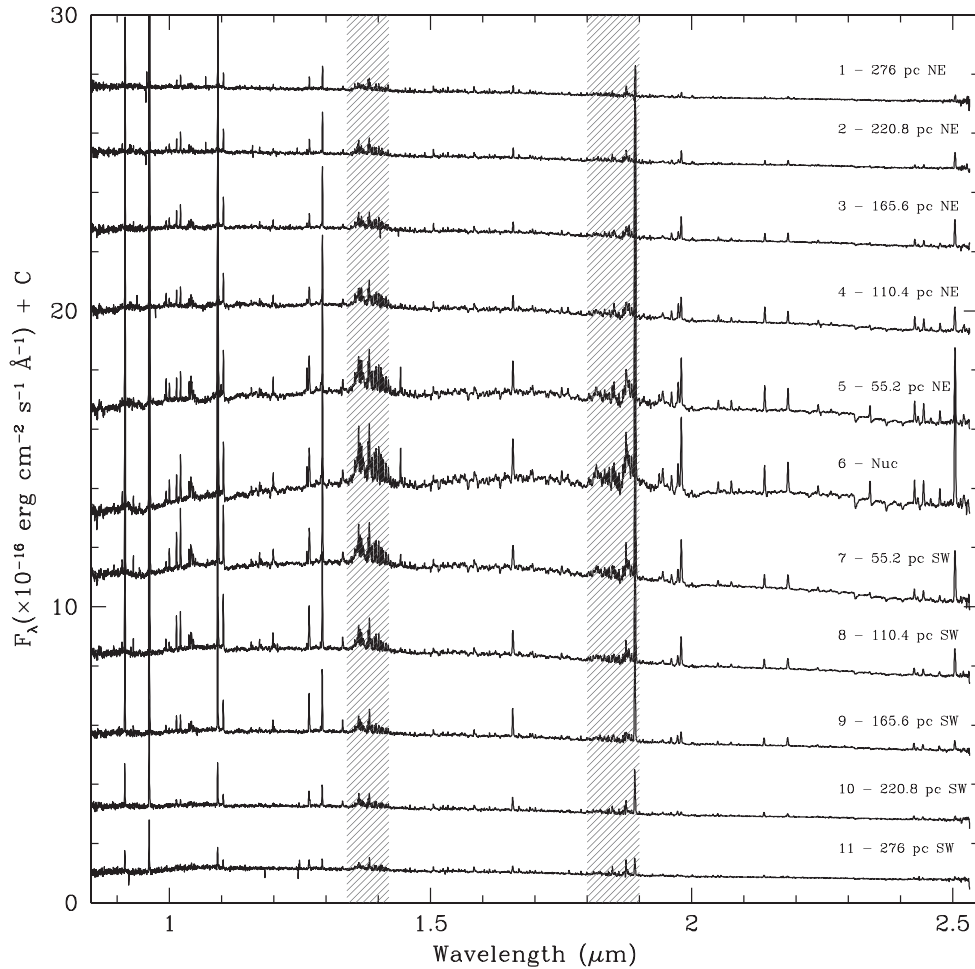
The very rich nuclear and extended emission-line spectrum found in the NIR for NGC 4388 is not surprising. Pogge (1988), using optical imaging and spectrophotometry, described the complex-

ity of the extended, ionized gas clouds surrounding the nucleus, reaching distances on the kiloparsec scale, well above the plane of the galaxy. When compared to other well-known Seyfert nuclei, NGC 4388 has one of the most richly structured circumnuclear regions yet observed. Our data offer a unique opportunity to extend and compare previous results on the kinematics and ionization structure of NGC 4388 based on molecular and low-ionization gas to the high-ionization gas covering a wide range of IPs.

### 3.1 Emission-line fluxes

In order to accurately measure weak emission lines, it is necessary to remove the stellar continuum. As we only wish to obtain a good representation of the stellar population itself, we fit the spectrum with the IRTF library of empirical stellar spectra (Cushing, Rayner &





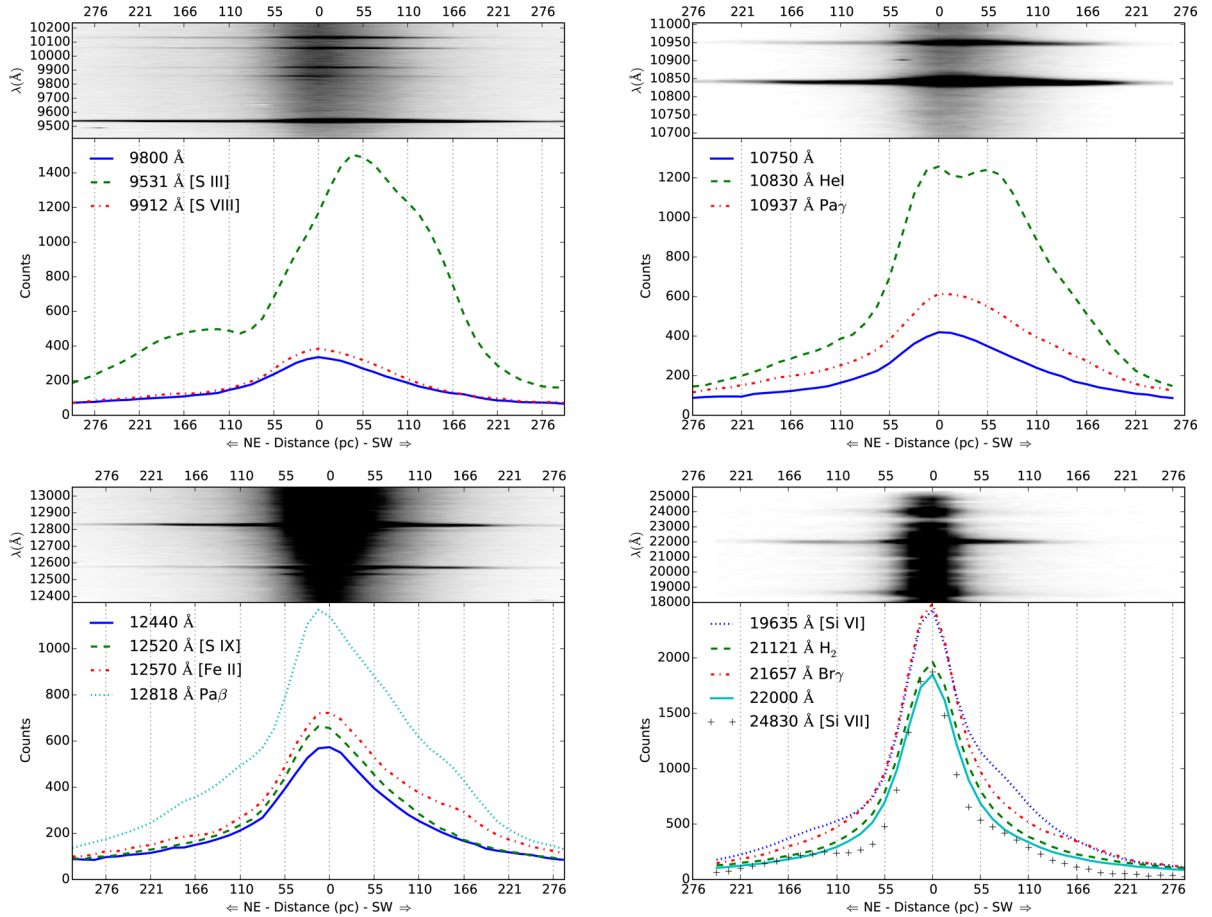
**Figure 3.** Nuclear and off-nuclear spectra extracted for NGC 4388. The shaded regions correspond to regions of low atmospheric transmission. The numbers at the right border correspond to the different apertures identified in Fig. 1, followed by the distance (in parsecs) from the nuclear aperture (denoted by ‘NUC’) to the centre of the corresponding extraction region.

Vacca 2005; Rayner, Cushing & Vacca 2009). This library contains 0.8–5.0  $\mu\text{m}$  spectra of 210 stars of spectral types F, G, K, M and S/C. We used a subset of 60 stars, removing similar spectra of stars with the same spectral types. To this, we added theoretical spectra of hotter stars ( $T_{\text{eff}} = 9000, 10\,000$  and  $20\,000$  K,  $\log g = 3.0$  and  $4.5$  dex, solar metallicity – calculated as in Coelho, private communication), which might be important if a younger stellar population is present in the galaxy. The stellar population modelling was done using the spectral synthesis code *STARLIGHT* (Cid Fernandes et al. 2004, 2005; Asari et al. 2007). In addition to the stars, we included a power law in the form of  $F_{\nu} \propto \nu^{-1.5}$  to represent the AGN featureless continuum. Extinction is modelled by *STARLIGHT* as due to foreground dust, and parametrized by the *V*-band extinction  $A_V$ . We use the Cardelli, Clayton & Mathis (1989) extinction law. To accurately model the stellar continuum, the emission lines are masked out of the fit. We also masked the regions of strong telluric absorption, where their correction was not possible, and the bluest part of the spectrum ( $\lambda \leq 9300$  Å), where the flux calibration can be most uncertain.

Examples of the fit obtained can be seen in Fig. 5, where the stellar template derived for the aperture 9, centred at 166 pc SW, can be observed. The observed spectrum (black line) is overlaid on the stellar population template (red line) followed by the residual

spectrum after removing the stellar population. The most conspicuous nebular emission line features are marked.

We measured line fluxes on the starlight-subtracted spectra using the LINER routine (Pogge & Owen 1993), a  $\chi$ -squared minimization algorithm which can fit simultaneously up to eight profile functions to a given line or set of blended lines. In addition, LINER also provides values for the peak position and the full width at half-maximum (FWHM) of each profile function fit. In NGC 4388, one Gaussian was necessary to represent the observed profiles for most lines. The exception was  $[\text{Fe II}] 1.257 \mu\text{m}$ , which required two Gaussians in the extractions from 55 pc SW from the centre and outwards. Examples of the Gaussian fit for  $[\text{Fe II}] 1.257 \mu\text{m}$  are shown in Fig. 6. The two uppermost panels, labelled (a) and (b), show the fit done in the apertures centred at 276 and 110 pc NE from the nucleus, respectively. Panel (c) shows the result for the nucleus. Note that only one component is evident in these spectra. In contrast, panels (d) to (h) display the best fit for the apertures where two Gaussian profiles were necessary to represent the iron line. Note the presence of the red component, which carries up to one third of the total  $[\text{Fe II}] 1.257 \mu\text{m}$  flux at some apertures.  $[\text{S IX}] 1.252 \mu\text{m}$  is well represented by a single Gaussian even at the positions where two components are employed for  $[\text{Fe II}] 1.257 \mu\text{m}$  (55 and 110 pc SW).  $[\text{Fe II}] 1.644 \mu\text{m}$ , the second brightest  $[\text{Fe II}]$  line, was fitted in all



**Figure 4.** Light distribution across the slit in the 2D data for different emission lines and continua observed in NGC 4388. Upper-left panel: [S III], [S VIII] and continuum at 9800 Å. Upper-right panel: He I, Pa $\gamma$  and continuum at 1.07  $\mu$ m. Bottom-left panel: [Fe II], Pa $\beta$ , [S IX] and continuum at 1.24  $\mu$ m. Bottom-right panel: [Si VI], H $_2$ , [Si VII], Br $\gamma$  and continuum at 2.2  $\mu$ m. In all panels, NE is to the left and SW is to the right. The dotted vertical lines in each panel mark the position of the centre each aperture extracted along the slit. Notice that the 2D combined frames used to produce these plots are not flux-calibrated. Therefore, relative intensities between different emission lines are not reliable here.

apertures by a single Gaussian. The lack of the red component in that line is probably due to the fact that it is intrinsically weaker than [Fe II] 1.257  $\mu$ m (by a factor of  $\sim 30$  per cent).

The fluxes of most lines changed little after subtracting the stellar component. The exceptions are [Ca VIII] 2.322  $\mu$ m, Pa $\gamma$  and He I 1.083  $\mu$ m. The former is severely affected by the CO band head at 2.324  $\mu$ m while the latter two lines sit over the broad CN band at 1.1  $\mu$ m.

The starlight-subtracted, integrated fluxes of the most conspicuous lines are reported in Table 1. The errors quoted are  $1\sigma$ , although a line was considered detected if it was above the  $3\sigma$  errors of the adjacent continuum. Upper limits are  $3\sigma$  representative.

### 3.2 Internal extinction distribution

The host galaxy of NGC 4388 is a nearly edge-on spiral with a dust lane crossing the nuclear region. Therefore, dust obscuration plays an important role in the interpretation of the galaxy structure. Optical imaging by Falcke et al. (1998) shows two wedges of reduced emission, demonstrating the presence of obscuring dust bands along the disc of this galaxy right into the nuclear region.

It is then necessary to quantify the amount of extinction towards the nucleus and in the circumnuclear region of NGC 4388 in order to determine the true luminosity of both the active nucleus and the

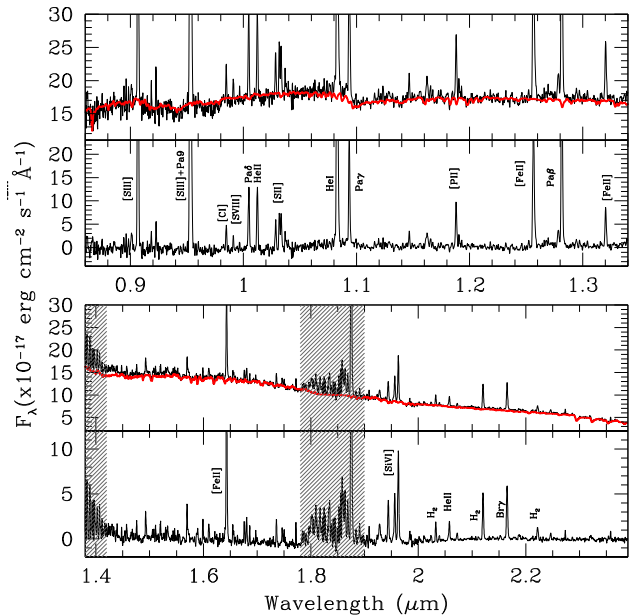
NLR. Large and small values have been reported in the literature for this source. Phillips & Malin (1982), for example, reported an  $E(B - V) = 0.5$  mag based on the H $\alpha$ /H $\beta$  ratio for the nucleus. Later, Colina (1992) found  $E(B - V) = 0.2$  and 0.6 mag in regions SW and NE of the nucleus, respectively, and a nuclear extinction of at least 0.3 mag. Petitjean & Durret (1993) found an  $E(B - V) = 0.32$  also from the Balmer decrement. However, few works on NGC 4388 in the literature have addressed this issue using NIR diagnostic lines, probably because of the lack of simultaneous observations covering at least two extinction sensitive lines.

The numerous H I and forbidden lines observed simultaneously in the spectra of NGC 4388, spanning a large interval in wavelength, allowed us to evaluate, for the first time, the intrinsic extinction affecting the nuclear and off-nuclear gas within the central  $\sim 550$  pc by means of several indicators. For this purpose, we used the Pa $\beta$ /Br $\gamma$ , Pa $\gamma$ /Br $\gamma$  and Pa $\delta$ /Br $\gamma$  flux line ratios and the expressions

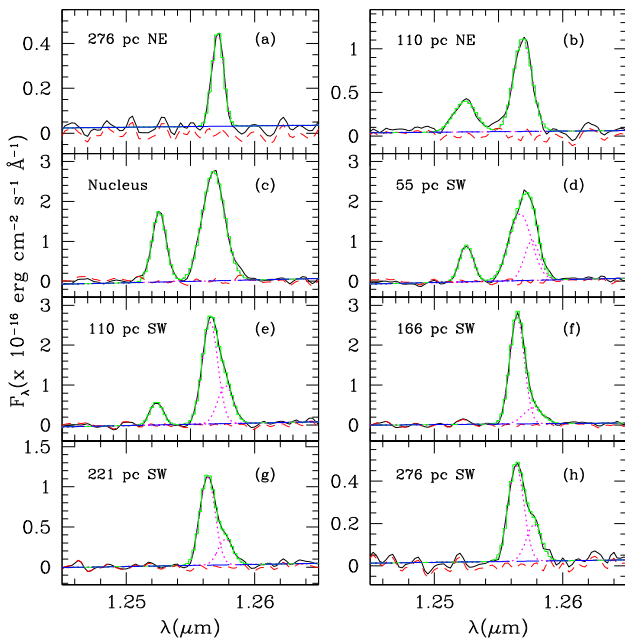
$$E(B - V)_{\text{Pa}\beta/\text{Br}\gamma} = 5.22 \times \log \left( \frac{5.88}{F_{\text{Pa}\beta}/F_{\text{Br}\gamma}} \right) \quad (1)$$

$$E(B - V)_{\text{Pa}\gamma/\text{Br}\gamma} = 3.46 \times \log \left( \frac{3.22}{F_{\text{Pa}\gamma}/F_{\text{Br}\gamma}} \right) \quad (2)$$

$$E(B - V)_{\text{Pa}\delta/\text{Br}\gamma} = 2.84 \times \log \left( \frac{2.0}{F_{\text{Pa}\delta}/F_{\text{Br}\gamma}} \right), \quad (3)$$



**Figure 5.** Example of the subtraction of the stellar population for the aperture centred at 166 pc SW of the nucleus. The observed spectrum (thin line) overlaid on the stellar population template (thick line) is shown followed by the spectrum free of stellar absorption features. The shadow areas correspond to regions of poor atmospheric transmission.  $z + J$  bands are in the upper panel while  $H + K$  bands are in the lower panel.



**Figure 6.** Examples of the Gaussian fitting for the  $[\text{Fe II}]$  1.257  $\mu\text{m}$  line. Panels (a) and (b) display the fitting done at 276 pc and 110 pc NE of the nucleus. In both apertures a single Gaussian was necessary. Panel (c) shows the fit done in nucleus. Panels (d) to (h) show the results for five apertures (all to the SW) where two Gaussians were required. In all cases, individual Gaussian components are in dotted lines. The histogram line shows the total fit. The dashed line is the residual after subtracting the fit. The full line is the observed data while the local fit to the continuum appears in long dash line. The emission feature to left of  $[\text{Fe II}]$  1.257  $\mu\text{m}$  is  $[\text{S IX}]$  1.252  $\mu\text{m}$ .

where  $F_{\text{Pa}\beta}$ ,  $F_{\text{Pa}\gamma}$ ,  $F_{\text{Pa}\delta}$  and  $F_{\text{Br}\gamma}$  are the observed emission-line fluxes of  $\text{Pa}\beta$ ,  $\text{Pa}\gamma$ ,  $\text{Pa}\delta$  and  $\text{Br}\gamma$ , respectively, listed in Table 1. In equations (1)–(3), the extinction law of Cardelli et al (1989) was adopted. The intrinsic ratios  $F_{\text{Pa}\beta}/F_{\text{Br}\gamma} = 5.88$ ,  $F_{\text{Pa}\gamma}/F_{\text{Br}\gamma} = 3.22$  and  $F_{\text{Pa}\delta}/F_{\text{Br}\gamma} = 2$ , corresponding to case B recombination (Osterbrock & Ferland 2006), were employed.

Fig. 7 and columns 2 to 4 of Table 2 show the values of  $E(B - V)$  found for the nuclear and off-nuclear apertures using the three different  $\text{H I}$  line ratios described above. Our results show that the region covered by the nuclear spectrum displays the highest amount of extinction,  $E(B - V) \sim 1.9$  mag. To the NE, from the nucleus to distances of  $\sim 150$  pc, the extinction remains large,  $\gtrsim 1$  mag. Farther out, it drops considerably, to  $E(B - V) = 0.6$ , becoming negligible at  $\sim 240$  pc. The large reddening found in the centre and the inner 150 pc to the NE is consistent with the system of dust lanes seen in the optical images of Pogge (1988) which obscures the northern portion of the galaxy. To the SW, right after crossing the nuclear region, the extinction drops steeply, reaching  $E(B - V) \sim 0.5$  at 150 pc. Farther out, it rises again, to 0.87 mag at 240 pc.

The very good match between the  $E(B - V)$  found from different indicators in most apertures indicates the consistency of our approach. Although some discrepancies are noted at some specific locations, overall differences of less than  $\sim 0.2$  mag between the minimum and maximum values of  $E(B - V)$  were observed.

In addition to the  $\text{H I}$  lines, there are a good number of  $[\text{Fe II}]$  lines in the NIR region which originate from radiative transitions involving levels within the  $3d^6 4s^4 D$  multiplet. Having more than one line from the same upper level is useful because their intrinsic line ratio becomes insensitive to density and temperature effects. Thus, they can be used as a dust extinction diagnostic. The strongest lines which fulfil this requirement and were detected in all apertures are 1.257 and 1.644  $\mu\text{m}$ . The intrinsic  $j_{1.257 \mu\text{m}}/j_{1.644 \mu\text{m}}$  ratio is estimated to be 1.25 with an accuracy of  $\sim 20$  per cent (Bautista et al. 2015). Extinction due to dust would decrease this ratio.

We employed the  $[\text{Fe II}]$  1.257  $\mu\text{m}/1.644 \mu\text{m}$  flux ratio measured along the different apertures in order to map the extinction affecting the region where that ion is formed. As for the  $\text{H I}$  lines, the law of Cardelli et al (1989) was adopted. The derived equation for  $E(B - V)$  employed is

$$E(B - V)_{[\text{Fe II}]} = 8.22 \times \log \left( \frac{1.25}{F_{1.257 \mu\text{m}}/F_{1.644 \mu\text{m}}} \right), \quad (4)$$

where  $F_{1.257 \mu\text{m}}$  and  $F_{1.644 \mu\text{m}}$  are the observed fluxes of  $[\text{Fe II}]$  1.257  $\mu\text{m}$  and  $[\text{Fe II}]$  1.644  $\mu\text{m}$ , respectively, listed in Table 1. In the apertures where two components were detected in the former line, we opted to sum up their fluxes. Although the presence of split lines may suggest separate kinematic systems, we are primarily assessing here extinction due to dust between the NLR and the observer. As both components are in the same line of sight, it is consistent to use the total flux observed. The values of  $E(B - V)$  derived using this indicator are listed in column 5 of Table 2 and plotted in Fig. 7 with a red dashed line.

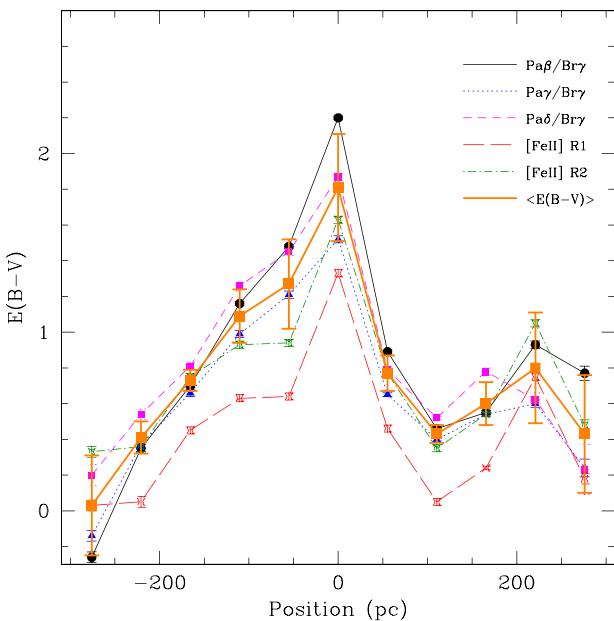
Although the overall shape of the dust distribution profile found for iron is very similar to that of hydrogen (see Fig. 7), our results point out that the reddening determined from the former, when adopting an intrinsic line ratio of 1.25, is considerably smaller than that of the latter. In the nucleus, for example, the difference in  $E(B - V)$  reaches 0.9 mag between both indicators. Similar estimates in the literature have found that the  $E(B - V)$  determined from the iron lines is significantly larger than that from hydrogen (Riffel,

**Table 1.** Integrated emission-line fluxes in units of  $10^{-15}$  erg cm $^{-2}$  s $^{-1}$  measured in the nuclear and off-nuclear apertures in NGC 4388.

| $N^a$ | $R$<br>(pc) | [S III]<br>$\lambda 9531$    | [C I]<br>$\lambda 9851$     | [S VIII]<br>$\lambda 9913$ | Pa $\delta$<br>1.005 $\mu$ m | He II<br>1.0124 $\mu$ m  | [S II]<br>1.032 $\mu$ m  | He I<br>1.083 $\mu$ m         | Pa $\gamma$<br>1.0937 $\mu$ m | [S IX]<br>1.252 $\mu$ m   |
|-------|-------------|------------------------------|-----------------------------|----------------------------|------------------------------|--------------------------|--------------------------|-------------------------------|-------------------------------|---------------------------|
| 1     | -276        | 7.21 $\pm$ 0.03              | <0.1                        | 0.14 $\pm$ 0.03            | 0.27 $\pm$ 0.03              | 0.40 $\pm$ 0.03          | 0.30 $\pm$ 0.06          | 1.84 $\pm$ 0.03               | 0.59 $\pm$ 0.03               | <0.1                      |
| 2     | -220.8      | 12.51 $\pm$ 0.04             | 0.14 $\pm$ 0.03             | 0.30 $\pm$ 0.04            | 0.55 $\pm$ 0.03              | 0.75 $\pm$ 0.03          | 0.82 $\pm$ 0.12          | 3.49 $\pm$ 0.03               | 1.01 $\pm$ 0.03               | 0.13 $\pm$ 0.02           |
| 3     | -165.6      | 17.53 $\pm$ 0.05             | 0.39 $\pm$ 0.04             | 0.53 $\pm$ 0.03            | 0.95 $\pm$ 0.03              | 1.18 $\pm$ 0.03          | 1.17 $\pm$ 0.15          | 6.26 $\pm$ 0.05               | 1.73 $\pm$ 0.05               | 0.21 $\pm$ 0.02           |
| 4     | -110.4      | 21.41 $\pm$ 0.06             | 0.59 $\pm$ 0.05             | 0.65 $\pm$ 0.07            | 1.29 $\pm$ 0.06              | 1.32 $\pm$ 0.06          | 1.75 $\pm$ 0.20          | 11.09 $\pm$ 0.10              | 2.59 $\pm$ 0.10               | 0.55 $\pm$ 0.07           |
| 5     | -55.2       | 36.27 $\pm$ 0.11             | 1.33 $\pm$ 0.07             | 1.17 $\pm$ 0.08            | 1.86 $\pm$ 0.09              | 1.88 $\pm$ 0.08          | 4.41 $\pm$ 0.34          | 27.40 $\pm$ 0.13              | 3.64 $\pm$ 0.13               | 1.85 $\pm$ 0.10           |
| 6     | 0           | 66.67 $\pm$ 0.10             | 1.13 $\pm$ 0.08             | 1.91 $\pm$ 0.08            | 2.71 $\pm$ 0.10              | 3.89 $\pm$ 0.10          | 6.55 $\pm$ 0.40          | 42.61 $\pm$ 0.15              | 5.82 $\pm$ 0.16               | 2.41 $\pm$ 0.15           |
| 7     | 55.2        | 71.20 $\pm$ 0.06             | 0.56 $\pm$ 0.08             | 1.88 $\pm$ 0.08            | 3.35 $\pm$ 0.10              | 4.93 $\pm$ 0.09          | 5.52 $\pm$ 0.23          | 41.65 $\pm$ 0.11              | 6.03 $\pm$ 0.11               | 1.16 $\pm$ 0.09           |
| 8     | 110.4       | 60.87 $\pm$ 0.08             | 0.88 $\pm$ 0.07             | 1.02 $\pm$ 0.08            | 2.93 $\pm$ 0.07              | 3.61 $\pm$ 0.07          | 4.43 $\pm$ 0.21          | 29.16 $\pm$ 0.09              | 5.25 $\pm$ 0.09               | 0.73 $\pm$ 0.07           |
| 9     | 165.6       | 29.51 $\pm$ 0.08             | 0.46 $\pm$ 0.04             | 0.23 $\pm$ 0.04            | 1.60 $\pm$ 0.06              | 1.54 $\pm$ 0.06          | 2.66 $\pm$ 0.22          | 13.85 $\pm$ 0.07              | 3.14 $\pm$ 0.07               | <0.24                     |
| 10    | 220.8       | 9.27 $\pm$ 0.06              | 0.13 $\pm$ 0.03             | 0.11 $\pm$ 0.03            | 0.73 $\pm$ 0.06              | 0.55 $\pm$ 0.04          | 0.60 $\pm$ 0.19          | 4.39 $\pm$ 0.04               | 1.20 $\pm$ 0.04               | <0.1                      |
| 11    | 276         | 4.17 $\pm$ 0.08              | <0.18                       | <0.13                      | 0.30 $\pm$ 0.09              | <0.17                    | 0.30 $\pm$ 0.13          | 1.52 $\pm$ 0.04               | 0.48 $\pm$ 0.04               | <0.09                     |
| $N^a$ | $R$<br>(pc) | [Fe II]<br>1.257 $\mu$ m     | Pa $\beta$<br>1.282 $\mu$ m | [Si X]<br>1.43 $\mu$ m     | [Fe II]<br>1.644 $\mu$ m     | [Si VI]<br>1.963 $\mu$ m | H $_2$<br>2.1218 $\mu$ m | Br $\gamma$<br>2.1657 $\mu$ m | [Ca VIII]<br>2.32 $\mu$ m     | [Si VII]<br>2.483 $\mu$ m |
| 1     | -276        | 0.47 $\pm$ 0.02              | 1.07 $\pm$ 0.02             | <0.08                      | 0.38 $\pm$ 0.02              | 0.27 $\pm$ 0.06          | 0.11 $\pm$ 0.01          | 0.16 $\pm$ 0.01               | <0.07                         | 0.41 $\pm$ 0.17           |
| 2     | -220.8      | 0.86 $\pm$ 0.04              | 2.15 $\pm$ 0.03             | <0.1                       | 0.70 $\pm$ 0.02              | 0.81 $\pm$ 0.06          | 0.28 $\pm$ 0.01          | 0.43 $\pm$ 0.01               | 0.12 $\pm$ 0.02               | 1.05 $\pm$ 0.12           |
| 3     | -165.6      | 1.02 $\pm$ 0.04              | 3.96 $\pm$ 0.03             | <0.2                       | 0.93 $\pm$ 0.03              | 1.51 $\pm$ 0.08          | 0.72 $\pm$ 0.02          | 0.92 $\pm$ 0.02               | 0.22 $\pm$ 0.02               | 2.08 $\pm$ 0.09           |
| 4     | -110.4      | 1.78 $\pm$ 0.07              | 6.33 $\pm$ 0.06             | <0.3                       | 1.70 $\pm$ 0.07              | 1.84 $\pm$ 0.13          | 2.07 $\pm$ 0.03          | 1.80 $\pm$ 0.03               | 0.32 $\pm$ 0.03               | 2.32 $\pm$ 0.13           |
| 5     | -55.2       | 3.87 $\pm$ 0.13              | 9.20 $\pm$ 0.10             | 1.58 $\pm$ 0.16            | 3.70 $\pm$ 0.11              | 2.77 $\pm$ 0.25          | 3.51 $\pm$ 0.05          | 3.01 $\pm$ 0.06               | 1.29 $\pm$ 0.03               | 4.07 $\pm$ 0.19           |
| 6     | 0           | 6.07 $\pm$ 0.24              | 13.80 $\pm$ 0.18            | 4.26 $\pm$ 0.24            | 7.05 $\pm$ 0.20              | 6.71 $\pm$ 0.58          | 4.78 $\pm$ 0.11          | 6.20 $\pm$ 0.13               | 4.17 $\pm$ 0.06               | 13.40 $\pm$ 0.41          |
| 7     | 55.2        | 3.66 $\pm$ 0.12 <sup>b</sup> | 12.64 $\pm$ 0.14            | 1.41 $\pm$ 0.13            | 4.69 $\pm$ 0.15              | 4.44 $\pm$ 0.36          | 2.50 $\pm$ 0.06          | 3.18 $\pm$ 0.08               | 1.45 $\pm$ 0.04               | 5.83 $\pm$ 0.26           |
|       |             | 1.49 $\pm$ 0.08              |                             |                            |                              |                          |                          |                               |                               |                           |
| 8     | 110.4       | 3.86 $\pm$ 0.09              | 10.81 $\pm$ 0.10            | <0.55                      | 4.29 $\pm$ 0.14              | 2.94 $\pm$ 0.17          | 1.64 $\pm$ 0.04          | 2.25 $\pm$ 0.05               | 0.57 $\pm$ 0.05               | 3.27 $\pm$ 0.15           |
|       |             | 1.43 $\pm$ 0.09              |                             |                            |                              |                          |                          |                               |                               |                           |
| 9     | 165.6       | 3.71 $\pm$ 0.09              | 6.97 $\pm$ 0.07             | <0.22                      | 3.82 $\pm$ 0.06              | 1.23 $\pm$ 0.12          | 1.20 $\pm$ 0.02          | 1.51 $\pm$ 0.03               | 0.19 $\pm$ 0.05               | 1.11 $\pm$ 0.15           |
|       |             | 0.76 $\pm$ 0.13              |                             |                            |                              |                          |                          |                               |                               |                           |
| 10    | 220.8       | 1.5 $\pm$ 0.06               | 2.35 $\pm$ 0.05             | <0.15                      | 2.05 $\pm$ 0.05              | 0.37 $\pm$ 0.10          | 0.65 $\pm$ 0.02          | 0.60 $\pm$ 0.03               | <0.06                         | 0.36 $\pm$ 0.10           |
|       |             | 0.58 $\pm$ 0.07              |                             |                            |                              |                          |                          |                               |                               |                           |
| 11    | 276         | 0.68 $\pm$ 0.05              | 0.76 $\pm$ 0.04             | <0.15                      | 0.82 $\pm$ 0.03              | 0.10 $\pm$ 0.05          | 0.24 $\pm$ 0.01          | 0.18 $\pm$ 0.02               | <0.06                         | 0.19 $\pm$ 0.08           |
|       |             | 0.29 $\pm$ 0.05              |                             |                            |                              |                          |                          |                               |                               |                           |

Notes. <sup>a</sup>Aperture number along the slit as identified in Fig. 1.

<sup>b</sup>When two entries are listed, the top one is the flux of the blue component and the bottom one that of the red component.



**Figure 7.** Values of  $E(B - V)$  derived from different H II line flux ratios as well as from the [Fe II] 1.257  $\mu$ m/1.644  $\mu$ m flux ratio using an intrinsic value of 1.25 (R1, long-dashed line) and 1.36 (R2, dash-dotted line) for the nuclear and off-nuclear apertures of NGC 4388. The thick solid line is the average extinction along the spatial direction. See the text for further details.

Rodríguez-Ardila & Pastoriza 2006; Mazzalay & Rodríguez-Ardila 2007; Martins et al. 2013). However, note that these works employed an intrinsic line ratio [Fe II] 1.257  $\mu$ m/[Fe II] 1.644  $\mu$ m of 1.36, as originally proposed by Bautista & Pradhan (1998). Column 6 of Table 2 lists the values of  $E(B - V)$  derived from equation (4) but adopting an intrinsic flux ratio of 1.36. It can be seen that the difference between the iron and hydrogen extinction decreases considerably. Indeed, it becomes indistinguishable at some positions. Note that the latter intrinsic flux ratio is still within the 20 per cent uncertainty determined by Bautista et al. (2015). Because the results found for [Fe II] using an intrinsic flux ratio of 1.36 better agree with that of H II, we opted for keeping these latter values.

Based on the  $E(B - V)$  values listed in columns 2 to 4 and column 6 of Table 2, we determined the average extinction for the inner 560 pc of NGC 4388. In this calculation, we employ the results found for the three H II ratios and that of iron assuming an intrinsic flux ratio of 1.36. The average extinction, at each aperture, is listed in the last column of Table 2 and also plotted in Fig. 7. The results confirm that the central regions of NGC 4388 are dusty, with the dust distributed inhomogeneously, peaking at the nucleus with an  $E(B - V)$  of  $1.81 \pm 0.3$  mag. It then decreases both to the NE and SW, although it remains high mainly to the NE. To the SW at 220 pc from the nucleus, we see a secondary peak which reaches  $0.85 \pm 0.3$  mag. Thanks to the reduced sensitivity of the NIR to dust, we are able to see, for the first time, emission from the NE side of the galaxy not observed before in the optical.



**Table 2.**  $E(B - V)$  derived in the nuclear and off-nuclear apertures in NGC 4388 using the emission-line flux ratios quoted in columns 2 to 6. Average values found are in column 7.

| $R$    | $\text{Pa}\beta/\text{Br}\gamma$ | $\text{Pa}\gamma/\text{Br}\gamma$ | $\text{Pa}\delta/\text{Br}\gamma$ | $[\text{Fe II}] (R1)^a$ | $[\text{Fe II}] (R2)^b$ | $\langle E(B - V) \rangle$ |
|--------|----------------------------------|-----------------------------------|-----------------------------------|-------------------------|-------------------------|----------------------------|
| -276   | $-0.26 \pm 0.03$                 | $-0.14 \pm 0.03$                  | $0.20 \pm 0.06$                   | $0.03 \pm 0.03$         | $0.33 \pm 0.03$         | $0.03 \pm 0.28$            |
| -220.8 | $0.35 \pm 0.02$                  | $0.37 \pm 0.02$                   | $0.54 \pm 0.03$                   | $0.05 \pm 0.03$         | $0.36 \pm 0.03$         | $0.41 \pm 0.09$            |
| -165.6 | $0.70 \pm 0.01$                  | $0.66 \pm 0.02$                   | $0.81 \pm 0.02$                   | $0.45 \pm 0.02$         | $0.75 \pm 0.02$         | $0.73 \pm 0.06$            |
| -110.4 | $1.16 \pm 0.01$                  | $0.99 \pm 0.02$                   | $1.26 \pm 0.02$                   | $0.63 \pm 0.02$         | $0.93 \pm 0.02$         | $1.09 \pm 0.15$            |
| -55.2  | $1.48 \pm 0.01$                  | $1.21 \pm 0.02$                   | $1.45 \pm 0.02$                   | $0.64 \pm 0.02$         | $0.94 \pm 0.02$         | $1.27 \pm 0.25$            |
| 0      | $2.20 \pm 0.01$                  | $1.52 \pm 0.02$                   | $1.87 \pm 0.02$                   | $1.33 \pm 0.02$         | $1.63 \pm 0.02$         | $1.81 \pm 0.30$            |
| 55.2   | $0.89 \pm 0.01$                  | $0.65 \pm 0.01$                   | $0.79 \pm 0.02$                   | $0.46 \pm 0.02$         | $0.77 \pm 0.02$         | $0.77 \pm 0.10$            |
| 110.4  | $0.46 \pm 0.01$                  | $0.40 \pm 0.01$                   | $0.52 \pm 0.01$                   | $0.05 \pm 0.02$         | $0.35 \pm 0.01$         | $0.43 \pm 0.05$            |
| 165.6  | $0.55 \pm 0.01$                  | $0.54 \pm 0.01$                   | $0.78 \pm 0.02$                   | $0.24 \pm 0.01$         | $0.54 \pm 0.02$         | $0.60 \pm 0.12$            |
| 220.8  | $0.93 \pm 0.02$                  | $0.60 \pm 0.02$                   | $0.62 \pm 0.04$                   | $0.75 \pm 0.02$         | $1.05 \pm 0.04$         | $0.80 \pm 0.31$            |
| 276    | $0.77 \pm 0.04$                  | $0.24 \pm 0.05$                   | $0.23 \pm 0.14$                   | $0.18 \pm 0.03$         | $0.48 \pm 0.14$         | $0.43 \pm 0.33$            |

Notes. <sup>a</sup>Values determined using an intrinsic line ratio  $[\text{Fe II}] 1.257 \mu\text{m}/1.644 \mu\text{m}$  of 1.25 (Bautista et al. 2015).

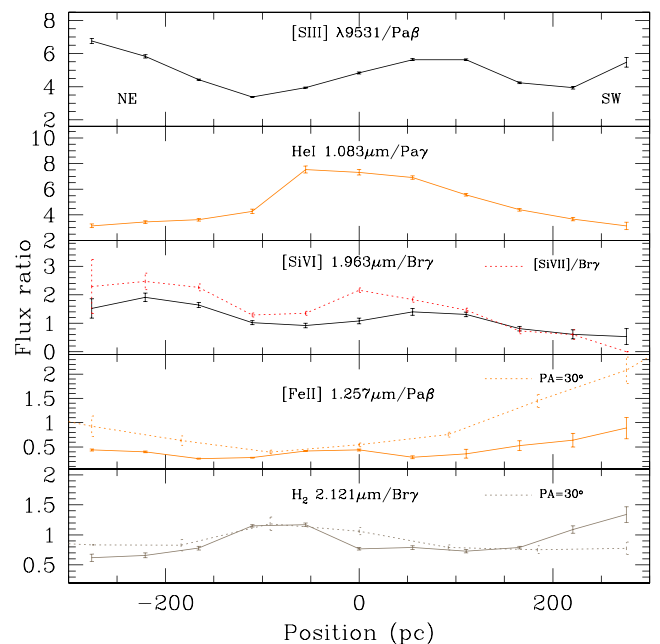
<sup>b</sup>Values determined using an intrinsic line ratio  $[\text{Fe II}] 1.257 \mu\text{m}/1.644 \mu\text{m}$  of 1.36 (Bautista & Pradhan 1998).

### 3.3 Emission-line ratios and excitation structure

The rich nuclear and extended emission-line spectra of NGC 4388 allow us to study how the gas ionization varies with distance to the central source as well as to gather information about the mechanisms which power these lines. Results obtained by means of imaging and long-slit spectroscopy reveal that line ratios like  $[\text{Fe II}]/\text{Pa}\beta$  and  $\text{H}_2/\text{Br}\gamma$  may vary dramatically on scales of 100 pc near the nuclei of Seyfert galaxies (Knop et al. 2001; Ramos Almeida et al. 2006; Mazzalay & Rodríguez-Ardila 2007; Mezcua et al. 2015). The analysis of these line ratios points to partially ionized regions created by X-ray photoionization from the nucleus or shocks from the interaction of outflowing gas, or both. This complex scenario has been confirmed in the last decade thanks to the gain in angular resolution provided by adaptive optics (AO) observations. The distinct flux distributions and kinematics of the  $\text{H}_2$ - and  $[\text{Fe II}]$ -emitting gas in nearby AGNs show that the former is more restricted to the plane of the galaxy, with the nuclear disc being fed by gas coming from the outer regions. The  $[\text{Fe II}]$  traces the outflows related to radio jets, evidenced by the highest velocity dispersion values (up to  $150 \text{ km s}^{-1}$ ) and the highest blueshifts and redshifts of up to  $500 \text{ km s}^{-1}$  of these lines when compared to the stellar rotation velocity or velocity dispersion of other emission lines (Riffel & Storchi-Bergmann 2011; Riffel, Storchi-Bergmann & Winge 2013; Mazzalay et al. 2015).

Most of the studies (including the ones with NGC 4388) aimed at studying the excitation mechanisms leading to the observed emission-line spectrum are restricted to the  $[\text{Fe II}]$  and  $\text{H}_2$  lines, and very few works have traced the gas distribution using emission lines which are usually the most prominent ones in the NIR region. This is the case of  $[\text{S III}] \lambda 9531$  and  $\text{He I } 1.083 \mu\text{m}$ . The former can be considered as the equivalent of  $[\text{O III}] \lambda 5007$  because of the similarity in the IP of both lines. The latter is emitted in a  $2^3\text{P}$  to  $2^3\text{S}$  transition and because of its small energy change ( $\Delta E = 1.14 \text{ eV}$ ), it is readily collisionally excited from the metastable  $2^3\text{S}$  triplet state. For that reason, it can potentially be a useful indicator of the density of the NLR.

Using the fluxes listed in Table 1, we have plotted in Fig. 8 the line flux ratios  $[\text{S III}]/\text{Pa}\beta$ ,  $\text{He I}/\text{Pa}\beta$ ,  $[\text{Si VI}]/\text{Br}\gamma$ ,  $[\text{Si VII}]/\text{Br}\gamma$ ,  $[\text{Fe II}]/\text{Pa}\beta$  and  $\text{H}_2/\text{Br}\gamma$ . For the  $[\text{Fe II}] 1.257 \mu\text{m}$  line, only the flux of the blue component was employed. As will be shown in Section 4, the gas emitting that component follows very closely the kinematics exhibited by  $\text{Pa}\beta$ , especially in the SW side, suggesting that these two lines are emitted by the same parcel of gas. In spite of the



**Figure 8.** Flux line ratios of the most conspicuous emission lines observed in NGC 4388. For  $[\text{Fe II}] 1.257 \mu\text{m}/\text{Pa}\beta$  and  $\text{H}_2 2.1218 \mu\text{m}/\text{Br}\gamma$ , values reported in the literature by Knop et al. (2001) using a  $\text{PA}=30^\circ$  are plotted for comparison purposes.

strong extinction affecting the circumnuclear region of NGC 4388, the ratios are formed by lines which are close enough in wavelength so that they are nearly or totally independent of the presence of dust. Except for the final two, these ratios have never been presented before for this source.

Overall, Fig. 8 confirms that the gas distribution in the inner 500 pc of NGC 4388 is highly inhomogeneous, with at least two regions of enhanced high-ionization emission lines: one in the centre, and another at  $\sim 250$  pc NE of the nucleus. Both the  $[\text{S III}]/\text{Pa}\beta$  and the silicon lines ( $[\text{Si VI}]$  and  $[\text{Si VII}]$ ) display high ratios at these locations, with values in the off-nuclear position as high as or higher than those in the nucleus. To the SW, the silicon lines drop considerably in intensity relative to  $\text{Br}\gamma$  from 100 pc of the nucleus to 280 pc.

These results are consistent with the optical maps of the central region of this source presented by Falcke et al. (1998). Their

uppermost right panel of Fig. 12 (and partially reproduced here in the right-hand panel of Fig. 1) displays WFPC2/*HST* H $\alpha$  emission for the inner 12 arcsec. In this image, a bright emission coincident with the nucleus and a faint cloud at RA = 12<sup>h</sup> 14<sup>m</sup> 76<sup>s</sup>; Dec. = 14° 56' 21" is observed. It should appear enhanced in the NIR because of the reduced sensitivity to dust. We associate the latter region with the highly-ionized peak detected at  $\sim$ 250 pc NE of the nucleus.

The behaviour of the He I line relative to hydrogen contrasts with what is seen with the higher ionization lines. It displays a flat peak in the central 100 pc and then drops steeply to the NE, reaching less than half the peak value at 270 pc. To the SW, the line ratio also decreases but more smoothly. If the line emissivity of He I 1.083  $\mu$ m is strongly dependent on the gas density, the results show a much larger gas density in the central region of NGC 4388.

The line ratios [Fe II]/Pa $\beta$  and H<sub>2</sub>/Br $\gamma$ , plotted in the last two panels (from top to bottom) of Fig. 8, confirm previous results presented by Knop et al. (2001) using *J*- and *K*-band spectroscopy. They employed a slit PA of 30°, very close to the orientation of the elongated, jet-like radio structure at PA=24°. Their results are also shown in Fig. 8 with dotted lines for comparison. For [Fe II]/Pa $\beta$ , both this work and Knop et al. data show an increase in the values of the ratio towards the SW, starting from the position where double-peaked iron lines show up, suggesting an extra source of line excitation. Knop et al. (2001) do not reported split iron lines. However, in their fig. 13, broad asymmetric iron lines SW of the nucleus can be noticed.

We interpret the enhancement of the [Fe II]/Pa $\beta$  ratio to the SW as direct evidence of shocks produced by the interaction between the radio jet and the interstellar medium (ISM) gas. The larger value of that ratio, relative to the one found in the nucleus, is more pronounced in the Knop et al. (2001) data than in ours. This is consistent with the fact that the slit in Knop et al. observations was nearly aligned to the elongated radio structure to the SW. To the NE, our data show a subtle decrease in the values of the ratio and then an increase 200 pc NE and outwards. The relationship between [Fe II] and radio emission is well known since Forbes & Ward (1993). They found that the strength of the former in the central regions of AGNs is tightly correlated with the 6 cm radio emission. This correlation has been widely confirmed by means of AO NIR IFU observations in several AGNs (Riffel & Storchi-Bergmann 2011; Riffel et al. 2015a; Riffel, Storchi-Bergmann & Riffel 2015b) at spatial scales of a few parsecs. All these works clearly evidence that the interaction of the radio jet with the gas produces wings in the [Fe II] line profiles at locations around the radio hotspots. In single-Gaussian fits, this effect appears as an enhancement of  $\sigma$ , similar to what is observed in the [Fe II] lines to the NE (see Section 4).

The line ratio H<sub>2</sub>/Br $\gamma$  shows values  $<1$  in most of the apertures, including the nucleus. The exception is the region between 50 and 100 pc NE of the AGN, when it increases to  $\sim$ 1.2 and at 200 pc SW and outwards, where it reaches 1.3. Our results agree to those reported by Knop et al. (2001) and Greene et al. (2014). They can be understood if we consider that most of the H<sub>2</sub> is located in a nuclear disc with a PA of 90°. As our slit is positioned along the edge of the ionization cone, both above and below the disc, the values of the ratio are low within the cone (H<sub>2</sub>/Br $\gamma$   $< 1$ ) and larger in the regions dominated by the disc (H<sub>2</sub>/Br $\gamma$   $> 1$ ).

The results discussed above highlight the very complex nature of the nuclear and circumnuclear region of NGC 4388. Our data reveal what is probably one of the best pieces of evidence of the intricate mixture of an AGN, a radio jet, dust and circumnuclear gas. The detection of split [Fe II] lines SW of the nucleus points out to this scenario. Shocks produced by the interaction between

the jet and the NLR gas enhanced this emission. Observations at superior angular resolution as provided by AO and sub-arcsecond radio observations of the jet with Very Large Array (VLA) would be helpful to unveil at greater detail this turbulent cauldron.

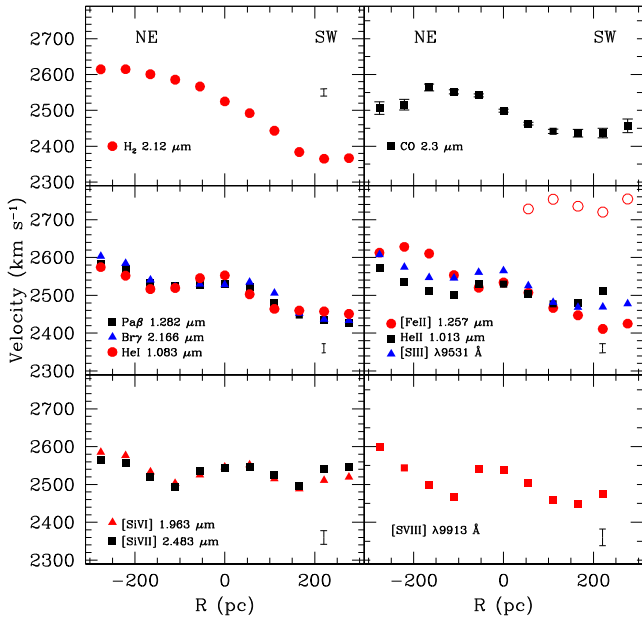
#### 4 STELLAR AND GAS KINEMATICS OF NGC 4388

The velocity and excitation structure of the NLR of NGC 4388 is widely known for being very complex (Corbin, Baldwin & Wilson 1988; Veilleux 1991) both at optical and radio wavelengths. It has been described by rotation plus outflow by several authors (e.g. Veilleux et al. 1999; Veilleux, Shopbell & Miller 2001; Greene et al. 2014). The radio-emission morphology suggests a collimated AGN-driven outflow reaching  $\sim$ 200 pc south of the nucleus (e.g. Stone et al. 1988; Falcke et al. 1998). The extended optical emission has two components: One associated with the galactic disc and another reaching 50 arcsec ( $\sim$ 4 kpc) above the galactic plane in the form of two opposite cones (Pogge 1988; Corbin et al. 1988; Falcke et al. 1998; Veilleux et al. 1999). The current scenario for this object is that the north edge of the galaxy is the near side. We see primarily the south ionization cone coming roughly towards us and the north-east ionization cone directed away from us. In the optical region, the north-east cone shows up only when it is no longer obscured by the disc. The reduced sensitivity of the NIR to dust allows that both the northern and southern components of the ionization cone can be observed.

The GNIRS data set allows us to extend our understanding of the stellar and gas kinematics of NGC 4388 by constructing position-velocity (PV) diagrams for extended line emission covering a wide range of species and IP. As shown by Fig. 4, the [S III]  $\lambda$ 9531, [S VIII]  $\lambda$ 9913, He I 1.083  $\mu$ m, He II 1.012  $\mu$ m, [Fe II] 1.257  $\mu$ m, Pa $\beta$ , H<sub>2</sub> 2.122  $\mu$ m, [Si VI] 1.963  $\mu$ m, Br $\gamma$  and [Si VII] 2.48  $\mu$ m lines extend all across the inner 560 pc in the NE–SW direction mapped by our slit, providing unique evidence of the gas kinematics around the nucleus. In particular, this list includes three very high ionization lines: [Si VI] 1.963  $\mu$ m, [Si VII] 2.48  $\mu$ m and [S VIII] 0.991  $\mu$ m. To the best of our knowledge, the latter two have not yet been used for this kind of analysis of this source. In absorption, the CO band heads provide information about the resolved stellar kinematics.

For each of the above emission lines, we measured their centroid position in each aperture by fitting a Gaussian function to the observed profile using the LINER routine as described in Section 3.1. To construct the PV diagram for the stellar component of NGC 4388, we used the penalized Pixel-Fitting (pPXF) method of Cappellari & Emsellem (2004) to fit the <sup>12</sup>CO and <sup>13</sup>CO stellar absorption band heads around 2.3  $\mu$ m and obtain the line-of-sight velocity distributions (LOSVD) of the stars. The pPXF outputs the radial velocity ( $V_*$ ), stellar velocity dispersion ( $\sigma_*$ ) and higher order Gauss–Hermite moments ( $h_{3*}$  and  $h_{4*}$ ), as well as the uncertainties for each parameter. As stellar template spectra we used those of the Gemini library of late spectral type stars observed with the GNIRS IFU and NIFS (Winge, Riffel & Storchi-Bergmann 2009), which contains the spectra of 60 late-type stars. The spectral resolution of the stellar templates (3.2 Å at 2.3  $\mu$ m) is better than that of our data. Therefore, we degraded the stellar templates to the same resolution as that of NGC 4388 before running the pPXF to measure the LOSVD.

We also derived the velocity dispersion  $\sigma$  for [S III], He I, [Fe II], Pa $\beta$ , [Si VI], H<sub>2</sub> as well as for the stellar continuum. For the emission lines, the velocity dispersion was derived from the FWHM found from the Gaussian fit when measuring the line centroid



**Figure 9.** PV diagrams for the different emission lines detected in NGC 4388. The top-right panel also shows the PV diagram for the stellar component derived from the CO stellar absorption lines at 2.3  $\mu\text{m}$ . The bar in each panel represents the largest uncertainty in the velocity, usually observed in the apertures close to the slit edges (apertures 1 and 11, centred at  $\pm 276$  pc NE and SW from the nucleus, respectively.) The two panels at the bottom of the figure map the velocity of the high-ionization lines. For the [Fe II] line (middle-right panel), filled circles represent the blue component while open circles are for the red component.

along the different apertures. This parameter was left to vary freely during the spectral fits, corrected in quadrature for the instrumental broadening, and then transformed into velocity dispersion using the relationship  $\sigma = \text{FWHM}/2.35$ .

The resulting PV diagrams, shown in Fig. 9, exhibit the complex kinematics of NGC 4388 already noted in optical and previous NIR spectroscopy of this source. In all emission lines except the CLs, a velocity amplitude of  $\sim 135 \text{ km s}^{-1}$  is clearly detected along the slit. However, only  $\text{H}_2$  2.121  $\mu\text{m}$  displays an organized velocity pattern, following a curve consistent with disc rotation. The amplitude of the velocity curve is largest in this line, reaching  $\sim 250 \text{ km s}^{-1}$ . This value is slightly larger than the one ( $\sim 175 \text{ m s}^{-1}$ ) found by van der Laan et al. (2013), who also obtained a rotation-like curve for this same line but at a different PA ( $90^\circ$ ).

The stellar component also displays rotation, but it is much flatter than that of the molecular gas, with a maximum amplitude of  $V_{\text{max}} \sim 60 \text{ km s}^{-1}$  at  $\sim 150$  pc from the nucleus. An organized pattern is also seen in the velocity dispersion of the stellar component, consistent with disc rotation and in agreement with that presented by Greene et al. (2014). While this is apparent in  $\text{H}_2$ , the stars are considerably dynamically hotter than the molecular gas, with the latter concentrated in a thinner disc than the former. The stellar  $\sigma$  also shows a feature not present in  $\text{H}_2$ : a drop in the dispersion field between 150 and 200 pc NE of the centre. At that location, a sudden decrease of nearly  $50 \text{ km s}^{-1}$  is observed. This feature is also reported by Greene et al. (2014). Because of their 2D view, they also found, on the same scale, a jump in velocity, PA and ellipticity, which they attributed to evidence of a transition from an inner disc to more bulge-dominated kinematics. For the particular case of NGC 4388, the most likely explanation of these observations

is that there is a disc within the inner 180 pc embedded in the larger scale bulge/bar.

From our data, the galaxy recession velocity derived for  $\text{H}_2$  2.121  $\mu\text{m}$  ( $V = 2525 \pm 5 \text{ km s}^{-1}$ ) in the nuclear aperture matches well, within uncertainties, the value reported in the literature using H I 21 cm observations:  $2524 \pm 1 \text{ km s}^{-1}$  (Lu et al. 1993). The best-fitting systemic velocity for the stellar component is  $2500 \pm 4 \text{ km s}^{-1}$ . This is  $25 \text{ km s}^{-1}$  smaller than the velocity found from the molecular gas. The reason for this difference is not clear but it is probably due to the fact that our data were taken with the slit at just one PA, far from the minor axis of the galaxy.

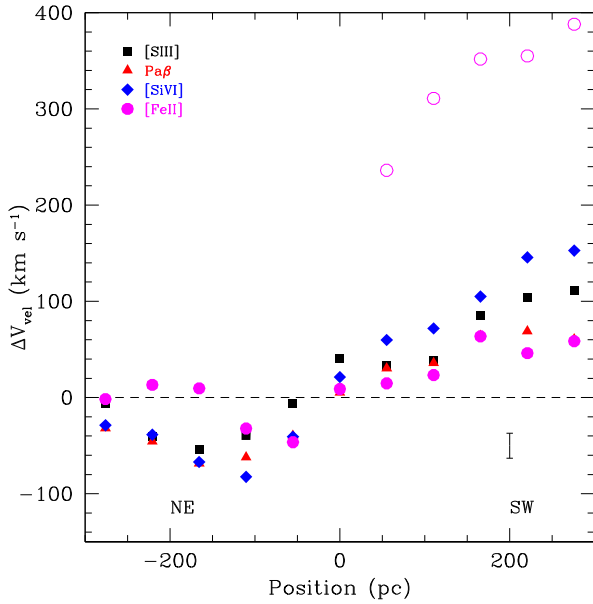
The observed recession velocities for Pa $\beta$  and Br $\gamma$  (in the nuclear aperture) are also in very good agreement ( $2530 \pm 5$  and  $2528 \pm 7 \text{ km s}^{-1}$ , respectively) with the systemic velocity of NGC 4388 derived from  $\text{H}_2$  2.121  $\mu\text{m}$ . For the remaining lines, redshifts relative to the systemic velocity at the galaxy nucleus were measured. The largest redshift is that of [S III] 0.953  $\mu\text{m}$ ,  $40 \text{ km s}^{-1}$  followed by He I 1.083  $\mu\text{m}$  ( $28 \text{ km s}^{-1}$ ). The high-ionization lines [Si VI] 1.963  $\mu\text{m}$ , [Si VII] 2.48  $\mu\text{m}$  and [S VIII] 0.991  $\mu\text{m}$  show, on average, redshifts of  $22 \text{ km s}^{-1}$ . The velocity amplitude measured in the inner 560 pc for these three lines is small: 66, 18 and  $69 \text{ km s}^{-1}$ , respectively.

Fig. 9 shows that all emission lines but [Fe II] are blueshifted NE of the nucleus and redshifted SW of it relative to  $\text{H}_2$  2.121  $\mu\text{m}$ . Moreover, the highly-ionized gas is non-rotation dominated. The case of [Fe II] is more complex. It is the only line which clearly display split profiles. The blue component follows closely the disc rotation with local perturbations at some positions filled circles in the middle-right panel of Fig. 9). The red peak which shows up to the SW (open circles) exhibits no sign of rotation and is strongly redshifted relative to both the molecular and ionized gas across the different apertures where it is detected.

Assuming that the galaxy rotation in the field of view (FOV) covered by our slit is well represented by the  $\text{H}_2$  2.121  $\mu\text{m}$  rotation curve, differences in velocity between the ionized and molecular gas at a given position can be interpreted as a departure of the ionized gas from the rotation of the galaxy's disc. This is illustrated in Fig. 10, where it is seen that [S III], [Si VI] H I and the red component of [Fe II] largely depart from pure disc rotation. The case of the latter line is extreme. The residual velocity increases steeply from  $240 \text{ km s}^{-1}$  at 55 pc SW of the nucleus to  $400 \text{ km s}^{-1}$  at 276 pc. The clouds emitting the red component of [Fe II] are clearly part of a distinct system, moving away from the observer. We propose here that this system is produced by interactions between the radio jet and the NLR gas. This is consistent with the radio-emission morphology, which suggests a collimated AGN-driven outflow reaching  $\sim 200$  pc south of the nucleus (Stone et al. 1988; Falcke et al. 1998).

The residual velocity exhibited by the highly-ionized gas in Fig. 10 confirms that the bulk of that emission is out of the nuclear disc, very likely distributed along the ionization cone. This hypothesis is consistent with the [Si VI] 1.963  $\mu\text{m}$  IFU maps presented by Greene et al. (2014) in their figs 5 and 7, where it can be seen that this emission runs preferentially at an angle of  $\approx 30^\circ$ , tracing the general orientation of the radio jet. The gas velocity for this line measured from our data at the different positions along the slit (PA =  $64^\circ$ ) matches that presented in Fig. 8 of Greene et al. (2014). This result, in combination with the excellent agreement between the PV curves of the CLs in Fig. 9, supports that the bulk of this emission is oriented in the direction of the radio jet, with very little gas in the nuclear disc.

Mid- and low-ionization lines ([S III], Pa $\beta$  and [Fe II]) show a more complex kinematics, reflecting the fact that they should be produced

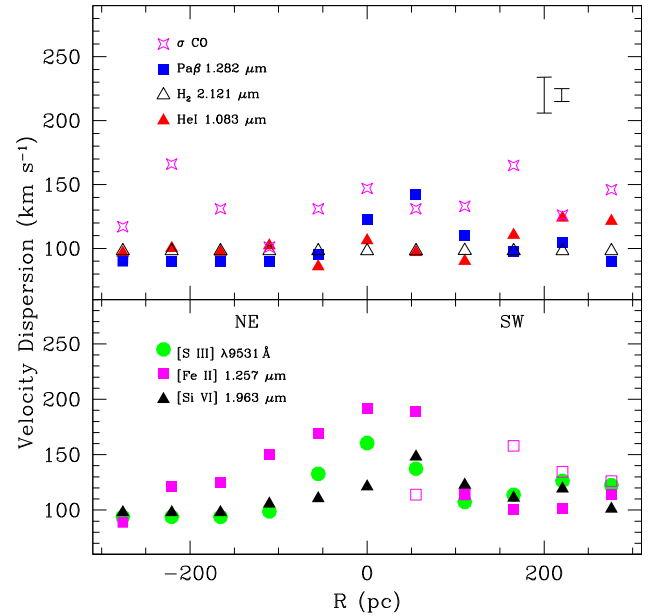


**Figure 10.** Difference between pure gas rotation (assumed to be represented by the H<sub>2</sub> PV curve of Fig. 9) and the gas velocity observed for [S III] (black squares), Paβ (red triangles) and [Si VI] (filled diamonds). For [Fe II], filled and open circles are for the blue and red components of the line, respectively. The bar at the bottom right represents the typical error bar of the measurements. The dashed line is for reference and indicates gas moving along with H<sub>2</sub>.

by gas distributed both along the disc and along the ionization cone. The blue peak of [Fe II], for example, follows closely the disc rotation of H<sub>2</sub> to the NE and up to 100 pc SW of the nucleus. Farther out to the SW, we see predominantly iron gas which lies along the ionization cone. In contrast, [S III] is primarily distributed along the ionization cone, although some sulphur gas should lie in the inner 100 pc of the nuclear disc. This is also the case for Paβ.

The blueshifted emission shown by the ionized gas relative to the molecular gas to the NE (see Fig. 10) along with the redshifted ionized emission SW of the nucleus, i.e. diametrically opposite to the blueshifted north-east complex, points out to a bipolar outflow of extraplanar gas. To the NE, bulk of this component is approaching us while to the SW it is moving away from us. Line splitting to the south-west clouds may reflect regions of high dissipation of kinetic energy caused by the interaction/deflection of the outflowing gas with ambient NLR gas. We are thus seeing in detail the inner 600 pc of the well-known outflow system of ionized material which extends to kiloparsec scales in this object.

The velocity dispersion of the gas,  $\sigma_{\text{gas}}$ , covers a broad range of values (see Fig. 11), with the largest ones occurring in or around the nucleus. [Fe II] 1.257  $\mu\text{m}$  is the line which displays the largest  $\sigma_{\text{gas}}$ , reaching 190 km s<sup>-1</sup> at the galaxy centre. Moreover, it systematically displays the largest values of velocity dispersion to the NE. [S III] also displays a maximum of  $\sigma_{\text{gas}}$  at the galaxy centre while  $\sigma_{\text{gas}}$  for [Si VI] and Paβ peaks at 55 pc SW of the nucleus. A similar result was also found for [Si VI], Paγ and Paδ, although for clarity they were omitted from Fig. 11. Note that 55 pc SW of the nucleus coincides with the location where [Fe II] 1.257  $\mu\text{m}$  splits into two components, suggesting that the kinematics of the ionized gas from this position and outwards is dominated by the outflow component. As was already pointed out in the literature (e.g. Riffel & Storchi-Bergmann 2011; Riffel et al. 2015a,b, and references therein), the interaction of the radio jet with the gas typically produces split [Fe II]



**Figure 11.** Velocity dispersion derived for the different emission lines observed as well as for the stellar CO band heads. The instrumental velocity resolution is 90 km s<sup>-1</sup>, meaning that H<sub>2</sub> is not resolved spectroscopically in any apertures. The bars at the top right of the plot indicate the maximum and average errors (1 $\sigma$ ) derived from the measurements. For [Fe II] (bottom panel), filled squares are for the blue component of the line while open squares are for the red component. At 110 pc SW, both components have the same width.

**Table 3.** Wavelengths, ionization potential (IP) and critical densities of the NIR CLs detected in NGC 4388.

| Ion                           | IP (eV) | log $n_e$ (cm <sup>-3</sup> ) |
|-------------------------------|---------|-------------------------------|
| [S VIII] 9913 Å               | 280.9   | 10.6                          |
| [S IX] 1.252 $\mu\text{m}$    | 328.8   | 9.4                           |
| [Si X] 1.423 $\mu\text{m}$    | 351.1   | 8.8                           |
| [Si VI] 1.963 $\mu\text{m}$   | 166.8   | 8.8                           |
| [Al IX] 2.045 $\mu\text{m}$   | 284.6   | 8.3                           |
| [Ca VIII] 2.321 $\mu\text{m}$ | 127.7   | 7.9                           |
| [Si VII] 2.48 $\mu\text{m}$   | 205     | 7.30                          |
| [Si IX] 3.94 $\mu\text{m}$    | 303     | 6.32                          |

profiles or an enhancement of  $\sigma$  in single-Gaussian fits at locations around the radio hotspots. Both effects are observed for [Fe II], giving further support to the role of shocks as an additional source of gas excitation in the central few hundred parsecs of NGC 4388.

In contrast to the ionized gas, molecular hydrogen displays velocity dispersion values of  $\sim 100$  km s<sup>-1</sup> across all the FOV of the slit. This reflects the fact that the bulk of this emission is concentrated in the nuclear disc. He I 1.083  $\mu\text{m}$  is the only ionized line which shows low values of  $\sigma_{\text{gas}}$ , at the limit of the spectral resolution. However, we noted an increase in the velocity dispersion at 166 pc SW of the nucleus and outwards.

No trend is observed between the velocity dispersion and the IP of the lines. A close inspection of Fig. 11 shows that He I is spectroscopically unresolved at all apertures while Paβ is only resolved in the nucleus and at 55 pc SW of it. [Si X], the line with the largest IP of all detected in NGC 3288 (see Table 3), is narrower than [Si VI] (100 and 120 km s<sup>-1</sup>, respectively). In contrast, [Fe II] is the broadest ionized line not only at the nucleus but also to the NE, being



resolved in nearly all apertures. Assuming that the gas is virialized, the lack of any correlation between IP and width of the lines implies that the NLR gas we see in NGC 4388 is no longer affected by the potential well of the central SMBH and instead primarily governed by the gravitational potential of the stars. Additional sources of line broadening such as shocks/outflows should become important, particularly in the circumnuclear region. Rodríguez-Ardila et al. (2011), in their study of the NIR properties of 51 AGNs, already noticed the lack of that correlation in some sources while in others it is clearly present.

In summary, the kinematics of the stellar and emission gas within the central 560 pc of NGC 4388 reveals the presence of a nuclear disc where the stars and molecular gas are distributed. In addition, a bipolar outflow of ionized gas is found to be distributed mostly outside the nuclear disc, along the direction of the radio jet. We also found evidence of an additional structure, probably a shell of gas, not revealed before and traced by [Fe II], very likely due to direct interaction between the NLR gas and the radio jet.

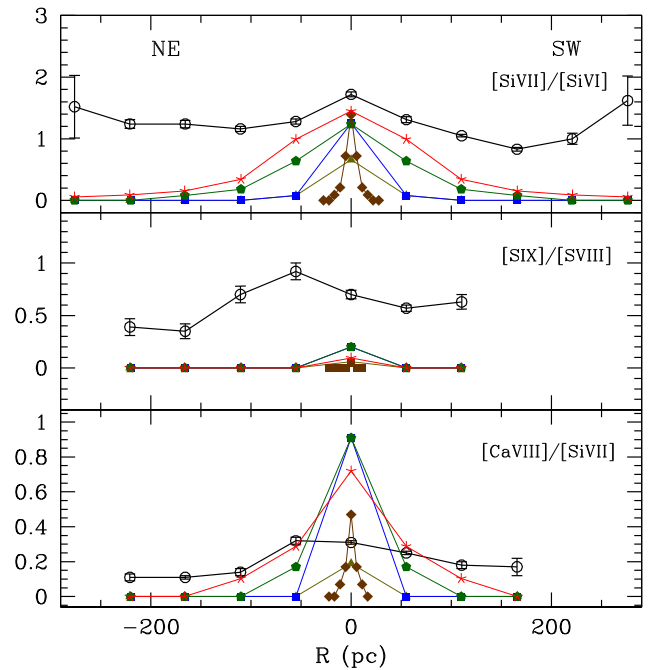
## 5 THE HIGH-IONIZATION LINE EMITTING GAS

Fig. 3 shows that NGC 4388 displays a remarkable high-ionization emission-line spectrum, with prominent lines seen not only in the nuclear but also in the off-nuclear apertures. In the wavelength interval covered by GNIRS, lines of [S VIII] 0.991  $\mu\text{m}$ , [S IX] 1.252  $\mu\text{m}$ , [Si X] 1.43  $\mu\text{m}$ , [Si VI] 1.963  $\mu\text{m}$ , [Al IX] 2.045  $\mu\text{m}$ , [Ca VIII] 2.32  $\mu\text{m}$  and [Si VII] 2.48  $\mu\text{m}$  were detected, some of them reported for the first time here. Lutz et al. (2002) had already reported the detection of [Si IX] 3.94  $\mu\text{m}$  in this object. All these lines span a large interval of IPs, from 127.7 eV ([Ca VIII]) up to 351.1 eV ([Si X], see Table 3). The spatial distribution of [S IX], [Al IX] and [Si X], the lines with the largest IPs, is essentially point-like, while [S VIII], [Si VI] and [Si VII] extend all over the inner  $\sim 560$  pc region covered by the GNIRS slit. Few objects in the literature reveal such an spatially extended CL spectrum. To be best of our knowledge, the only comparable examples are NGC 1068 (Mazzalay et al. 2013) and Mrk 78 (Ramos Almeida et al. 2006).

The conspicuous CL spectrum in the NIR contrasts strongly with the modest high-ionization spectrum in the optical region. Pogge (1988) and Veilleux (1991), for example, did not detect [Fe VII]  $\lambda 6087$  (IP = 97 eV), a CL which is typically strong in AGN CL emitters, although Colina (1992) does report it in his integrated nuclear spectrum. Moreover, the Sloan Digital Sky Survey (SDSS) spectrum of this object reveals the presence of [Fe VII] at  $\lambda\lambda 5721$  and 6084 and very likely, [Fe X]  $\lambda 6374$ .

To the best of our knowledge, this is the first simultaneous detection of all the above NIR lines in NGC 4388. The fact that three silicon lines ([Si VI], [Si VII] and [Si X]) and two sulphur lines ([S VIII] and [S IX]) with different degrees of excitation are present in this AGN allows us to construct line ratios between ions of the same atom which are independent of the metallicity of the gas. Very few sources with a positive detection of at least four out of the five lines above are found in the literature (Oliva et al. 1994; Riffel et al. 2006; Ramos Almeida, Pérez García & Acosta-Pulido 2009; Martins et al. 2010; Mason et al. 2015).

All the above makes NGC 4388 an optimal target to study the relationship between coronal emission and the physical conditions suitable for their formation. It is known that extended, soft X-ray emission coincident in extension and overall morphology with the [O III]  $\lambda 5007$  emission is observed in this object (Bianchi et al. 2006). Does this high-energy emission provide sufficient photons



**Figure 12.** Line flux ratios [Si VII]/[Si VI] (upper panel), [S IX]/[S VIII] (middle panel) and [Ca VIII]/[Si VII] (bottom panel) versus distance from the active nucleus. Observations are marked with open circles. They were corrected for extinction according to the values of  $E(B - V)$  listed in column 7 of Table 2 and assuming the law of Cardelli et al (1989). Filled symbols are model predictions of CLOUDY for gas clouds with no dust and density  $n_{\text{H}} = 500 \text{ cm}^{-3}$  (stars),  $n_{\text{H}} = 10^3 \text{ cm}^{-3}$  (pentagons),  $n_{\text{H}} = 10^4 \text{ cm}^{-3}$  (squares) and  $n_{\text{H}} = 10^5 \text{ cm}^{-3}$  (diamonds). See the text for other parameters employed in the models.

to ionize the gas and produce the extended CL spectrum observed? Rodríguez-Ardila et al. (2011), for instance, found that CL emission becomes stronger with increasing nuclear X-ray emission (soft and hard). This result would indicate photoionization as the dominant excitation mechanism for the high-ionization lines. However, this trend holds only when considering Type 1 sources alone; it gets weaker or vanishes when including Type 2 sources, very likely because the X-ray emission measured in the latter is not the intrinsic ionizing continuum.

Given the difference in IP between the CLs listed in Table 3, their flux ratios are useful to map the ionization structure and mechanisms powering them. Fig. 12 shows, in open circles and from top to bottom, the observed [Si VII]/[Si VI], [S IX]/[S VIII] and [Ca VIII]/[Si VII] line flux ratios in the different apertures where these lines were detected at the  $3\sigma$  level. Note that the first two ratios are insensitive to abundance effects while the last one was proposed by Ferguson, Korista & Ferland (1997) as a reliable abundance indicator. The three line flux ratios shown for each aperture were corrected for extinction assuming the  $E(B - V)$  listed in column 7 of Table 2 and the law of Cardelli et al (1989).

For [Si VII]/[Si VI] (upper panel of Fig. 12), the largest value in the ratio is found in the nuclear region, where it reaches  $1.7 \pm 0.04$ . Outside the nucleus, to the NE, the distribution is nearly flat, with values close to 1.25. Towards the SW, this ratio decreases smoothly from the centre, reaching  $\sim 1$  at 220 pc. Overall, [Si VII]/[Si VI] varies from  $\sim 0.8$  to  $\sim 1.7$  in the inner 550 pc from the nucleus. The [S IX]/[S VIII] ratio (middle panel of Fig. 12) peaks at  $\sim 55$  pc NE of the NIR nucleus, where a line flux ratio of  $0.9 \pm 0.2$  is measured. Further to the NE, it decreases sharply, down to  $0.4 \pm 0.07$  at

~166 pc. In the opposite direction, it decreases smoothly, down to ~0.6 at 150 pc from the peak. The distribution of values for this ratio is clearly asymmetric. Moreover, [S IX] is significantly more extended towards the NE than to the SW. It is observed up to distances of ~220 pc NE of the centre. In contrast, it is detected up to ~110 pc to the SW.

The bottom panel of Fig. 12 displays [Ca VIII]/[Si VII]. As with the previous line ratio, it peaks at 50 pc NE of the nucleus, with a value of  $0.32 \pm 0.02$ . Farther out, it decreases sharply, falling to about one third of the peak value and remaining nearly constant up to ~220 pc NE, where [Ca VIII] is no longer detected. Towards the SW, the values of that line ratio at the different apertures decrease smoothly relative to the peak, reaching  $0.17 \pm 0.05$  at 166 pc. This ratio is also distributed asymmetrically.

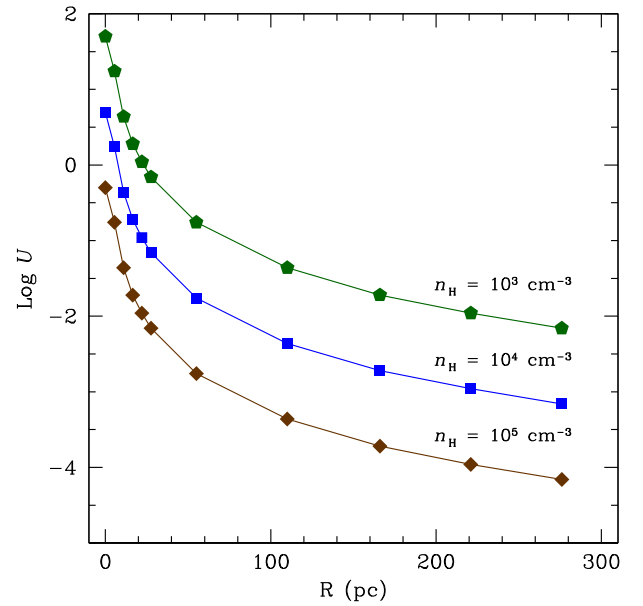
Ferguson et al. (1997) presented the results of a large number of photoionization simulations of coronal emission lines in AGNs, with the ionization parameter  $U(H)$  being the fundamental parameter of their models. They found that CLs form at distances from just outside the broad-line region to  $\sim 400L_{43.5}^{1/2}$  pc, where  $L_{43.5}$  is the ionizing luminosity in units of  $10^{43.5}$  erg  $s^{-1}$ , in gas with ionization parameter  $-2.0 < \log U(H) < 0.75$ . This suggests that CLs form close to the nucleus in high-density gas and further out from the nucleus in lower density gas. The models provide the peak equivalent width of each line. Since that quantity is referenced to the same point in the incident continuum, ratios between the equivalent widths of different lines should indicate grossly their expected relative strengths.

Using table 1 of Ferguson et al. (1997), a [Si VII]/[Si VI] ratio of 1.2 is predicted. This value is about 40 per cent smaller than the one observed in nucleus of NGC 4388 and is similar to the ratios observed at distances larger than 100 pc. However, Ferguson et al. models refer to the peak in the equivalent width distribution, which occurs at distances of a few parsecs from the central source and gas density  $> 10^6$   $cm^{-3}$ . At distances of about 100 pc, the predicted equivalent width of [Si VII] drops to just a few angstroms, implying weak emission lines, close to the detection limit. This strongly contrasts with our observations at these distances, with equivalent widths of tens of angstroms. Sulphur and calcium CLs are not that bright as those of silicon but the gas which emits them in NGC 4388 also extends to scales of a few hundred of parsecs.

To further investigate whether photoionization by the central source can be responsible for the observed CL ratios, we followed the multi-cloud approach presented by Kraemer & Crenshaw (2000). To this aim, we generated a grid of models using CLOUDY (version C013.03; Ferland et al. 2013).

The input to the models includes the gas density  $n_H$ , the distance of the clouds to the nucleus  $R$ , the AGN luminosity, the spectral energy distribution of the ionizing radiation, the elemental abundances, the dust/gas ratio and the column density of the emission-line clouds. Solar abundances from Grevesse et al. (2010) were employed in all cases. The numerical abundances relative to hydrogen are as follows: He =  $8.51 \times 10^{-2}$ , C =  $2.69 \times 10^{-4}$ , O =  $4.9 \times 10^{-4}$ , N =  $6.76 \times 10^{-5}$ , Ne =  $8.51 \times 10^{-5}$ , S =  $1.32 \times 10^{-5}$ , Si =  $3.24 \times 10^{-5}$ , Mg =  $3.98 \times 10^{-5}$  and Fe =  $3.16 \times 10^{-5}$ . No other values of abundances were used as no reliable indicators of that quantity exist using NIR lines. Moreover, evidence of gas with solar abundances in this source has been reported using optical and X-ray observations (Yoshida et al. 2004; Shirai et al. 2008).

The ionizing continuum employed was similar to that deduced by Mathews & Ferland (1987). It is meant to represent a typical radio-quiet AGN continuum and consists of several broken power laws of the form  $f_\nu \propto \nu^\alpha$  with  $\alpha$  taking different values according to the



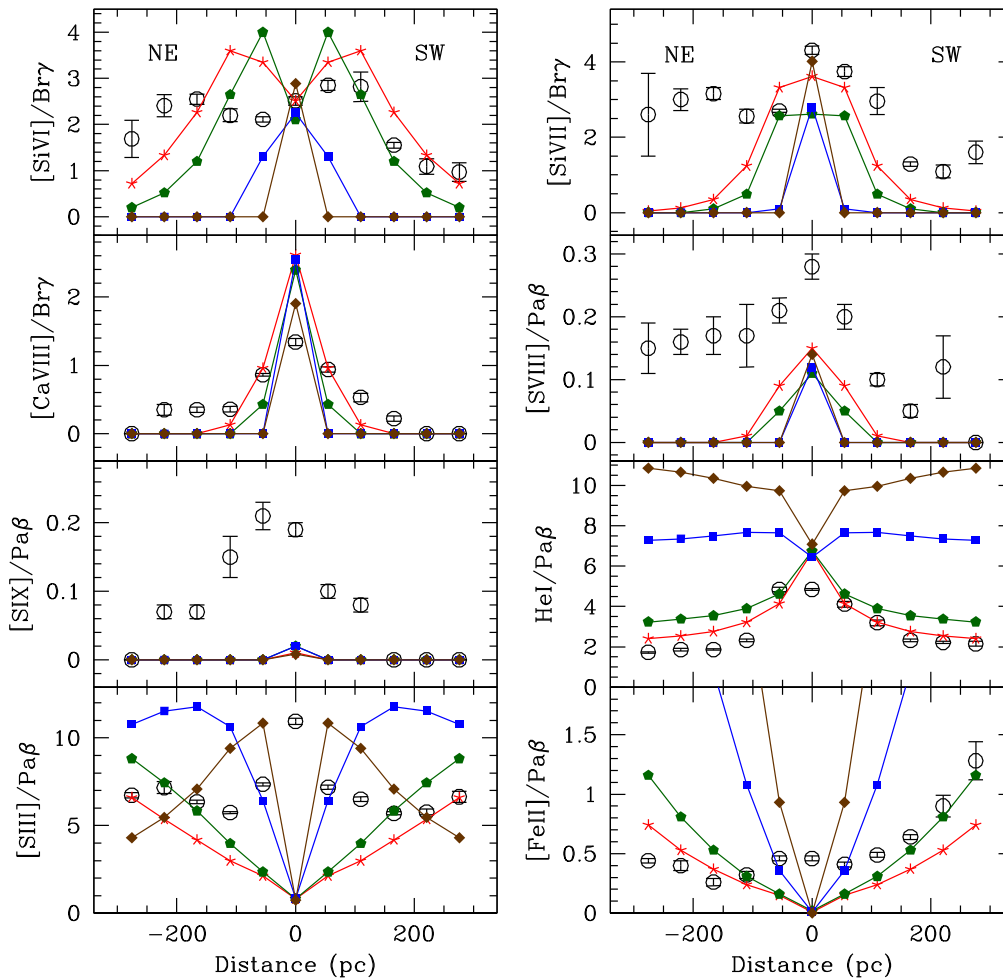
**Figure 13.** Variation of the log of the ionization parameter,  $\log U$ , with the distance from the centre of the AGN for clouds of density  $n_H = 10^3$ ,  $10^4$  and  $10^5$   $cm^{-3}$ . The symbols are the same employed in Fig. 12.

wavelength range. The intrinsic luminosity of NGC 4388 above the Lyman limit,  $1.26 \times 10^{44}$  erg  $s^{-1}$ , was estimated by Vasudevan et al. (2013). This value is typical of Seyfert 1 nuclei (Pier et al. 1994), and was employed in all models. Clouds with densities  $n_H = 500$ ,  $10^3$ ,  $10^4$ ,  $10^5$  and  $10^6$   $cm^{-3}$  were considered at distances  $R$  varying from a fraction of a parsec to ~270 pc from the nucleus, covering the range of distances mapped by our observations.

Fig. 12 displays the model predictions for clouds with gas density  $n_H = 500$   $cm^{-3}$  (stars),  $10^3$   $cm^{-3}$  (filled pentagons),  $10^4$   $cm^{-3}$  (filled squares) and  $10^5$   $cm^{-3}$  (filled diamonds) for the three CL ratios already described at the different apertures extracted in NGC 4388. Results for clouds of  $n_H = 10^6$   $cm^{-3}$  are not shown as they produce CLs only for the nuclear aperture. Filled triangles show the predictions for clouds of  $n_H = 10^4$   $cm^{-3}$ , assuming depletions of elements from gas phase with a size distribution and abundance similar to the ISM of our Galaxy. Fig. 13 shows the variation of the ionization parameter  $U$  with the distance from the centre for clouds of density  $n_H = 10^3$ ,  $10^4$  and  $10^5$   $cm^{-3}$ . The symbols are the same as those displayed in Fig. 12.

An inspection of the [Si VII]/[Si VI] line ratio in Fig. 12 shows that all models, regardless of the density, peak at a similar value of that ratio (~1.4). The main difference among them is in the size of the emission region as well as the value of the ionization parameter. High-density clouds ( $n_H > 10^4$   $cm^{-3}$ ) produce very compact [Si VII] and [Si VI] emission regions, peaking at the nucleus and extending only to the central few tens of parsecs. The ionization parameter for these clouds is high but still within the expected conditions of the NLR. In contrast, lower density clouds ( $n_H = 500$  and  $10^3$   $cm^{-3}$ ) emit silicon up to distances of a few hundred of parsecs. However, in the innermost few parsecs, the ionization parameter for these latter clouds is rather high, up to two orders of magnitude higher than that expected for NLR clouds.

We found that a suitable combination of clouds of density  $n_H = 500$ ,  $10^3$ ,  $10^4$  and  $10^5$   $cm^{-3}$  are able to reproduce the observed values (open circles) within the central 55 pc from the nucleus. At larger distances, these clouds do not produce enough [Si VII] to sustain the large values of that ratio compatible to the observations.



**Figure 14.** Emission-line flux ratios versus distance from the active nucleus. Observations are marked with open circles. They were corrected for extinction according to the values of  $E(B - V)$  listed in column 7 of Table 2 and assuming the Cardelli et al (1989) law. Filled symbols are model predictions of CLOUDY for gas clouds with no dust and density  $n_{\text{H}} = 500 \text{ cm}^{-3}$  (stars),  $n_{\text{H}} = 10^3 \text{ cm}^{-3}$  (pentagons),  $n_{\text{H}} = 10^4 \text{ cm}^{-3}$  (squares) and  $n_{\text{H}} = 10^5 \text{ cm}^{-3}$  (diamonds). See the text for other parameters employed in the models.

At 110 pc, for instance, low-density clouds ( $n_{\text{H}} \leq 10^3 \text{ cm}^{-3}$ ) can account for only 30 per cent of the observed ratio while at 160 pc and farther away, they are responsible for less than 10 per cent of the observed values. Note that we have assumed that the clouds in all apertures are not coplanar. Therefore, no screening of one cloud by the other takes place. This warrants that all clouds are illuminated by the same AGN continuum. We also assume that the CLs are emitted preferentially by these clouds. This may not be the case for mid- and low-ionization lines, for which clouds not facing directly the central source may also contribute to the observed flux.

CLOUDY predictions for  $[\text{S IX}]/[\text{S VIII}]$  are shown in the middle panel of Fig. 12. It can be seen that all models, regardless of the density, underpredict the observations. The observed extinction-corrected ratio at the nucleus is  $0.7 \pm 0.04$  while clouds with  $n_{\text{H}} = 10^4 \text{ cm}^{-3}$  predict a ratio of 0.2. Moreover, none of the clouds considered are able to form  $[\text{S IX}]$  and  $[\text{S VIII}]$  at distances larger than 55 and 110 pc, respectively, from the centre. This strongly contrasts with our observations, as we detect  $[\text{S VIII}]$  as far as 221 pc NE and SW of the nucleus. The gas emitting  $[\text{S IX}]$  is less extended than that of  $[\text{S VIII}]$  to the SW but yet it is detected up to 110 pc from the AGN. Thus, clouds with suitable physical conditions for the NLR fail at reproducing our data. It is important to mention that the values for that ratio in NGC 4388 do not appear to be unusual among AGN.

For example, NGC 1068 shows sulphur CL ratios rather similar to those of NGC 4388 in its nuclear and extended NLR (Martins et al. 2010). Moreover, the observed sulphur ratios in NGC 4388 are also well within the distribution of values for that ratio presented by Rodríguez-Ardila et al. (2011) in their study of CLs in 54 AGNs. Thus, sulphur CL emission poses a challenge to photoionization by the central source.

Model results for  $[\text{Ca VIII}]/[\text{Si VII}]$  show that clouds with  $n_{\text{H}} \sim 10^4 - 5 \text{ cm}^{-3}$  reproduce the data points at the nucleus while lower density clouds dominate the emission of highly ionized calcium farther out. Note, however, that CLOUDY is unable to produce  $[\text{Ca VIII}]$  at distances larger than 110 pc while that ion is detected up to 220 pc NE and 160 pc SW in NGC 4388. Ferguson et al. (1997) proposed the  $[\text{Ca VIII}]/[\text{Si VII}]$  line flux ratio as a suitable abundance indicator. Assuming solar abundances, the models reproduce consistently the observations up to the point where  $[\text{Ca VIII}]$  is theoretically produced. Optical and X-ray observations (Yoshida et al. 2004; Shirai et al. 2008) had already pointed out solar metallicity in the nucleus of NGC 4388. Our results support these previous findings.

In order to check the consistency of our results, we have compared high-, mid- and low-ionization lines to hydrogen recombination lines. The results are shown in Fig. 14, where eight different ratios

**Table 4.** Predicted emission-line ratios from model components, composite and observations for the nuclear aperture.

| Line ratio            | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d</sup> |
|-----------------------|----------------------|----------------------|------------------------|-----------------------|
| [S III]/Pa $\beta$    | 0.83                 | 0.73                 | 0.78                   | 10.95 $\pm$ 0.18      |
| [S VIII]/Pa $\beta$   | 0.12                 | 0.14                 | 0.13                   | 0.28 $\pm$ 0.02       |
| [S II]/Pa $\beta$     | 0.07                 | 0.06                 | 0.07                   | 0.83 $\pm$ 0.05       |
| He I/Pa $\beta$       | 6.44                 | 7.1                  | 6.8                    | 4.84 $\pm$ 0.11       |
| [S IX]/Pa $\beta$     | 0.02                 | 0.01                 | 0.02                   | 0.19 $\pm$ 0.01       |
| [Fe II]/Pa $\beta$    | 0.12                 | 0.0                  | 0.06                   | 0.46 $\pm$ 0.02       |
| [Si X]/Pa $\beta$     | 0.06                 | 0.0                  | 0.03                   | 0.26 $\pm$ 0.01       |
| [Si VI]/Br $\gamma$   | 2.25                 | 2.89                 | 2.57                   | 2.51 $\pm$ 0.09       |
| [Si VII]/Br $\gamma$  | 2.8                  | 4.02                 | 3.41                   | 4.31 $\pm$ 0.11       |
| [Ca VIII]/Br $\gamma$ | 2.54                 | 1.9                  | 2.22                   | 1.34 $\pm$ 0.05       |
| [Si VII]/[Si VI]      | 1.25                 | 1.39                 | 1.32                   | 1.7 $\pm$ 0.04        |
| [S IX]/[S VIII]       | 0.2                  | 0.07                 | 0.14                   | 0.7 $\pm$ 0.04        |
| [Si X]/[Si VI]        | 0.16                 | 0.0                  | 0.08                   | 0.55 $\pm$ 0.05       |
| [Ca VIII]/[Si VII]    | 0.91                 | 0.47                 | 0.69                   | 0.31 $\pm$ 0.01       |

Notes. <sup>a</sup> $U = 0.7$ ;  $R = 3.2$  pc;  $n_{\text{H}} = 10^4$  cm<sup>-3</sup>.

<sup>b</sup> $U = -0.3$ ;  $R = 3.2$  pc;  $n_{\text{H}} = 10^5$  cm<sup>-3</sup>.

<sup>c</sup>50 per cent cloud A, 50 per cent cloud B.

<sup>d</sup>Dereddened;  $E(B - V) = 1.81 \pm 0.3$ ;  $\text{Pa}\beta = 5.5 \pm 0.06 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

are plotted. Observed data are represented by open circles while the models follow the same convention employed in Fig. 12. A rapid inspection of Fig. 14 reveals that for most CLs the models strongly underpredict the observations for apertures  $\sim 150$  pc and farther away from the centre. At these same positions, low- and mid-ionization lines are well covered by CLOUDY.

It is possible, by suitably combining clouds of different physical conditions weighted by their contribution to the total flux, to fit the observed emission-line ratios displayed in Figs 12 and 14 at each aperture. This multi-component approach is based on the evidence that components of different densities at the same radial distances exist in the NLR. It has been successfully employed in the literature (Schulz & Komossa 1993; Kraemer & Crenshaw 2000) to model the NLR and extended NLR of AGNs. Tables 4–9 list the predicted line ratios at the nucleus and at the off-nuclear apertures. The composite flux was obtained after combining the output of two given pairs of models plotted in Figs 12 and 14. For simplicity, we have limited ourselves to a two-component model (named cloud A and cloud B), although we are aware that this is a degenerate problem, so that multiple solutions for each aperture are possible. The main goal here is to illustrate the range of physical conditions necessary to fit the coronal and low- to mid-ionization lines.

An inspection of Table 4 shows that clouds of  $n_{\text{H}} = 10^4$  and  $10^5$  cm<sup>-3</sup>, located at  $\sim 3$  pc from the centre, are able to reproduce the line ratios measured in the nucleus of NGC 4388. The good agreement found between model predictions and observations for most line ratios points out that photoionization by the AGN is the main source of excitation for the nuclear gas.

Farther out, at 55 pc from the centre (see Table 5), photoionization by the AGN is still able to reproduce most of the observations. However, the density of the clouds responsible for the production of the emission lines must be lower than that in the nucleus,  $n_{\text{H}} \leq 10^3$  cm<sup>-3</sup>. Indeed, a larger contribution of clouds with  $n_{\text{H}} = 500$  cm<sup>-3</sup> (70 per cent by weight) was found. As can be observed in Fig. 14, clouds with  $n_{\text{H}} \geq 10^4$  cm<sup>-3</sup> produce negligible or no CLs at all at that position. At 110 pc from the AGN, the bulk of clouds responsible for the production of high-ionization lines is dominated by low-density clouds, of  $n_{\text{H}} \approx 500$  cm<sup>-3</sup>. This result is shown in Table 6. It can also be seen that CLOUDY underpredicts by a factor of

**Table 5.** Predicted emission-line ratios from model components, composite and observations at 55 pc NE and SW of the AGN.

| Line ratio            | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d,e</sup>            |
|-----------------------|----------------------|----------------------|------------------------|------------------------------------|
| [S III]/Pa $\beta$    | 2.12                 | 2.35                 | 2.19                   | 7.35 $\pm$ 0.09<br>7.19 $\pm$ 0.12 |
| [S VIII]/Pa $\beta$   | 0.15                 | 0.05                 | 0.14                   | 0.21 $\pm$ 0.02<br>0.2 $\pm$ 0.02  |
| [S II]/Pa $\beta$     | 0.06                 | 0.07                 | 0.06                   | 0.79 $\pm$ 0.02<br>0.56 $\pm$ 0.01 |
| He I/Pa $\beta$       | 4.14                 | 4.62                 | 4.28                   | 4.84 $\pm$ 0.11<br>4.11 $\pm$ 0.14 |
| [S IX]/Pa $\beta$     | 0.0                  | 0.0                  | 0.0                    | 0.21 $\pm$ 0.02<br>0.10 $\pm$ 0.01 |
| [Fe II]/Pa $\beta$    | 0.15                 | 0.16                 | 0.15                   | 0.46 $\pm$ 0.02<br>0.41 $\pm$ 0.02 |
| [Si VI]/Br $\gamma$   | 3.35                 | 4.0                  | 3.55                   | 2.11 $\pm$ 0.06<br>2.85 $\pm$ 0.11 |
| [Si VII]/Br $\gamma$  | 3.32                 | 2.57                 | 3.10                   | 2.70 $\pm$ 0.04<br>3.74 $\pm$ 0.13 |
| [Ca VIII]/Br $\gamma$ | 0.96                 | 0.43                 | 0.8                    | 0.86 $\pm$ 0.02<br>0.94 $\pm$ 0.04 |
| [Si VII]/[Si VI]      | 1.0                  | 0.64                 | 0.89                   | 1.28 $\pm$ 0.04<br>1.31 $\pm$ 0.05 |
| [S IX]/[S VIII]       | 0.0                  | 0.0                  | 0.0                    | 0.92 $\pm$ 0.08<br>0.57 $\pm$ 0.03 |
| [Ca VIII]/[Si VII]    | 0.29                 | 0.17                 | 0.25                   | 0.32 $\pm$ 0.02<br>0.25 $\pm$ 0.01 |

Notes. <sup>a</sup> $U = -0.46$ ;  $R = 55$  pc;  $n_{\text{H}} = 500$  cm<sup>-3</sup>.

<sup>b</sup> $U = -0.76$ ;  $R = 55$  pc;  $n_{\text{H}} = 10^3$  cm<sup>-3</sup>.

<sup>c</sup>70 per cent cloud A, 30 per cent cloud B.

<sup>d</sup>The first entry corresponds to the NE aperture while the second one to the SW aperture.

<sup>e</sup>Dereddened;  $E(B - V)_{\text{NE}} = 1.27 \pm 0.25$ ;  $E(B - V)_{\text{SW}} = 0.77 \pm 0.1$ ;  $\text{Pa}\beta_{\text{NE}} = 2.34 \pm 0.03 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>;  $\text{Pa}\beta_{\text{SW}} = 2.31 \pm 0.04 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

2–3 the observations of CLs, pointing out that either a more complex approach is needed or that photoionization by the AGN starts failing at sustaining the production of high-ionization lines. Low-ionization lines, in contrast, are well reproduced by the models. Their production is largely favoured by clouds of  $n_{\text{H}} \leq 10^3$  cm<sup>-3</sup>, giving further support to our results. Recall that [S III] 9531 Å and He I 1.083  $\mu\text{m}$  are the strongest lines detected in all apertures.

Tables 7–9 show that at 166 pc and farther away from the AGN, photoionization by the central source alone is no longer able to reproduce the observations of high-ionization lines: CLOUDY predicts line ratios which are one order of magnitude smaller than the observations or it is unable to produce them. Indeed, at 221 pc, clouds with  $n_{\text{H}} \leq 10^3$  cm<sup>-3</sup> are unable to produce CLs while they still sustain the production of low- to mid-ionization lines. We also tested models with clouds of gas density as low as  $n_{\text{H}} = 200$  cm<sup>-3</sup>. This latter value was derived by Colina (1992) from the optical [S II]  $\lambda\lambda 6717, 6731$  doublet in NGC 4388 for a projected distance of 380 pc from the nucleus and agrees with the density found by Petitjean & Durret (1993) at a similar distance from the central source. Although such clouds do produce CLs, the predicted line ratio [Si VII]/[Si VI] is 0.21. That is, a factor of  $\sim 5$  lower than observed.

The inclusion of dusty clouds (although appealing for several reasons) does not help to improve the fits. The model which takes them into account, shown in Fig. 12, produces too little CL emission that its contribution appears to be negligible in the central apertures. We also tested models with other values of densities for that type of clouds with similar results as those shown here. Ferguson et al.



**Table 6.** Predicted emission-line ratios from model components, composite and observations at 110 pc NE and SW of the AGN.

| Line ratio            | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d,e</sup>            |
|-----------------------|----------------------|----------------------|------------------------|------------------------------------|
| [S III]/Pa $\beta$    | 3                    | 3.9                  | 3.09                   | 5.74 $\pm$ 0.06<br>6.51 $\pm$ 0.13 |
| [S VIII]/Pa $\beta$   | 0.09                 | 0.0                  | 0.09                   | 0.17 $\pm$ 0.05<br>0.10 $\pm$ 0.01 |
| [S II]/Pa $\beta$     | 0.06                 | 0.09                 | 0.06                   | 0.44 $\pm$ 0.01<br>0.22 $\pm$ 0.03 |
| He I/Pa $\beta$       | 3.22                 | 3.9                  | 3.29                   | 2.32 $\pm$ 0.06<br>3.19 $\pm$ 0.14 |
| [S IX]/Pa $\beta$     | 0.0                  | 0.0                  | 0.0                    | 0.15 $\pm$ 0.03<br>0.08 $\pm$ 0.01 |
| [Fe II]/Pa $\beta$    | 0.24                 | 0.31                 | 0.25                   | 0.32 $\pm$ 0.03<br>0.49 $\pm$ 0.02 |
| [Si VI]/Br $\gamma$   | 3.6                  | 2.7                  | 3.51                   | 2.20 $\pm$ 0.14<br>2.82 $\pm$ 0.32 |
| [Si VII]/Br $\gamma$  | 1.24                 | 0.49                 | 1.17                   | 2.56 $\pm$ 0.18<br>2.96 $\pm$ 0.36 |
| [Ca VIII]/Br $\gamma$ | 0.13                 | 0.0                  | 0.12                   | 0.36 $\pm$ 0.04<br>0.53 $\pm$ 0.06 |
| [Si VII]/[Si VI]      | 0.34                 | 0.18                 | 0.32                   | 1.16 $\pm$ 0.04<br>1.05 $\pm$ 0.2  |
| [S IX]/[S VIII]       | 0.0                  | 0.0                  | 0.0                    | 0.70 $\pm$ 0.08<br>0.63 $\pm$ 0.07 |
| [Ca VIII]/[Si VII]    | 0.1                  | 0.0                  | 0.09                   | 0.14 $\pm$ 0.02<br>0.18 $\pm$ 0.02 |

Notes. <sup>a</sup> $U = -1.06$ ;  $R = 110$  pc;  $n_{\text{H}} = 500$  cm<sup>-3</sup>.

<sup>b</sup> $U = -1.36$ ;  $R = 110$  pc;  $n_{\text{H}} = 10^3$  cm<sup>-3</sup>.

<sup>c</sup>90 per cent cloud A, 10 per cent cloud B.

<sup>d</sup>The first entry corresponds to the NE aperture while the second one to the SW aperture.

<sup>e</sup>Dereddened;  $E(B - V)_{\text{NE}} = 1.09 \pm 0.15$ ;  $E(B - V)_{\text{SW}} = 0.43 \pm 0.05$ ;  $\text{Pa}\beta_{\text{NE}} = 1.44 \pm 0.02 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>;  $\text{Pa}\beta_{\text{SW}} = 1.5 \pm 0.03 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

(1997) had already demonstrated that dust in regions of large  $U$  absorbs much of the incident continuum. This greatly reduces the strength of the CLs, implying that they must be formed in nearly dust-free gas. Thus, under this scenario, most of the extinction affecting the observed spectra should be produced by dust located outside of the CL region (CLR).

We should also note that the line flux ratio [Si X]/[Si VI] (or [Si X]/Pa $\beta$ ) is strongly underestimated by the models (see Table 4). Recall that [Si X] is detected only in the nuclear aperture. For the assumed luminosity and form of the ionizing continuum, sufficient [Si X] relative to [Si VI] is produced if the emitting clouds are located 0.3 pc or closer to the AGN. That is, a factor of 10 closer to the central source than the value assumed. This implies that the bulk of [Si X] is produced in the boundaries of the broad-line region and the torus. The [Si X]/[Si VI] ratio is also a robust indicator of the form of the input ionizing continuum because of the large difference in ionization potential of the lines involved ( $\Delta\text{IP} = 184$  eV). A better fit to the observations can be obtained if the clouds emitting [Si X] are illuminated by a harder continuum than that of the other CLs.

Although it is clear that photoionization by the central source accounts for most of the observed CL strengths not only in the nucleus but in regions as far as 110 pc away of it, at larger distances the model outputs largely underpredict our observations. This suggests that additional mechanisms should be present to enhance the high-ionization spectrum observed. In the previous sections, we found that the high-ionization gas is primarily distributed along the elongated nuclear radio structure, tracing an outflow which extends up

**Table 7.** Predicted emission-line ratios from model components, composite and observations at 166 pc NE and SW of the AGN.

| Line ratio            | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d,e</sup>            |
|-----------------------|----------------------|----------------------|------------------------|------------------------------------|
| [S III]/Pa $\beta$    | 4.2                  | 6                    | 4.68                   | 6.35 $\pm$ 0.10<br>5.70 $\pm$ 0.09 |
| [S VIII]/Pa $\beta$   | 0.01                 | 0.0                  | 0.01                   | 0.17 $\pm$ 0.03<br>0.05 $\pm$ 0.01 |
| [S II]/Pa $\beta$     | 0.08                 | 0.0                  | 0.10                   | 0.37 $\pm$ 0.05<br>0.64 $\pm$ 0.03 |
| He I/Pa $\beta$       | 2.8                  | 3.60                 | 3.04                   | 1.87 $\pm$ 0.04<br>2.32 $\pm$ 0.06 |
| [S IX]/Pa $\beta$     | 0.0                  | 0.0                  | 0.0                    | 0.07 $\pm$ 0.01                    |
| [Fe II]/Pa $\beta$    | 0.4                  | 0.54                 | 0.44                   | 0.26 $\pm$ 0.03<br>0.64 $\pm$ 0.02 |
| [Si VI]/Br $\gamma$   | 2.3                  | 1.20                 | 1.97                   | 2.55 $\pm$ 0.11<br>1.55 $\pm$ 0.06 |
| [Si VII]/Br $\gamma$  | 0.3                  | 0.10                 | 0.24                   | 3.16 $\pm$ 0.16<br>1.29 $\pm$ 0.06 |
| [Ca VIII]/Br $\gamma$ | 0.0                  | 0.0                  | 0.0                    | 0.35 $\pm$ 0.04<br>0.22 $\pm$ 0.04 |
| [Si VII]/[Si VI]      | 0.16                 | 0.08                 | 0.14                   | 1.24 $\pm$ 0.06<br>0.83 $\pm$ 0.03 |
| [S IX]/[S VIII]       | 0.0                  | 0.0                  | 0.0                    | 0.35 $\pm$ 0.07<br>...             |
| [Ca VIII]/[Si VII]    | 0.0                  | 0.0                  | 0.0                    | 0.11 $\pm$ 0.01<br>0.17 $\pm$ 0.05 |

Notes. <sup>a</sup> $U = -1.42$ ;  $R = 166$  pc;  $n_{\text{H}} = 500$  cm<sup>-3</sup>.

<sup>b</sup> $U = -1.72$ ;  $R = 166$  pc;  $n_{\text{H}} = 10^3$  cm<sup>-3</sup>.

<sup>c</sup>70 per cent cloud A, 30 per cent cloud B.

<sup>d</sup>The first entry corresponds to the NE aperture while the second one to the SW aperture.

<sup>e</sup>Dereddened;  $E(B - V)_{\text{NE}} = 0.73 \pm 0.06$ ;  $E(B - V)_{\text{SW}} = 0.60 \pm 0.12$ ;  $\text{Pa}\beta_{\text{NE}} = 6.84 \pm 0.08 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>;  $\text{Pa}\beta_{\text{SW}} = 10.9 \pm 0.13 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

to 200 pc SW of the nucleus. Moreover, the presence of split components, such as the ones we detected in [Fe II], evidences interaction between the radio jet and the ambient gas. Greene et al. (2014) presented examples of [Si VI] 1.963  $\mu\text{m}$  emission-line profiles along the ionized cone, giving additional support to this scenario. It then makes sense to consider the role of shocks produced by interactions between the radio jet or a radially accelerated outflow and the ISM to enhance the high-ionization line strengths in the off-nuclear apertures. Note, for example, that Kraemer & Crenshaw (2000) showed the necessity of fast shocks ( $\sim 1000$  km s<sup>-1</sup>) at distances larger than 100 pc from the nucleus in NGC 1068 to explain the high [Ne V] and [Fe VII] strengths relative to H $\beta$  measured in that object. No suitable combination of clouds powered by photoionization by the central source could explain the observed ratios.

The models of Contini & Viegas (2001, hereafter CV01) are useful to test the effects of shocks coupled to photoionization by the central source; even in the presence of shocks, the effect of the central continuum cannot be ignored. In their modelling, CV01 considered that the clouds are moving outwards from the galaxy centre, with the shock front forming on the outer edge of the cloud, whereas the ionizing radiation reaches the opposite edge which faces the active centre. The ionization due to both the primary radiation (from the central source) and the diffuse radiation generated by the free-free and free-bound transitions of the shocked and photoionized gas, as well as the collisional ionization, are all accounted for. The shock velocity  $V_s$  and the ionizing flux from the central source at the Lyman limit reaching the cloud,  $F_{\text{h}}$  (in units of cm<sup>-2</sup> s<sup>-1</sup> eV<sup>-1</sup>), are

**Table 8.** CL ratios from model and observations at 221 pc NE and SW of the AGN.

| Line ratio            | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d,e,f</sup>          |
|-----------------------|----------------------|----------------------|------------------------|------------------------------------|
| [S III]/Pa $\beta$    | 5.40                 | 7.40                 | 6.20                   | 7.17 $\pm$ 0.34<br>5.78 $\pm$ 0.16 |
| [S VIII]/Pa $\beta$   | 0.0                  | 0.0                  | 0.0                    | 0.16 $\pm$ 0.02<br>0.12 $\pm$ 0.05 |
| [S II]/Pa $\beta$     | 0.10                 | 0.20                 | 0.14                   | 0.45 $\pm$ 0.12<br>0.34 $\pm$ 0.08 |
| He I/Pa $\beta$       | 2.53                 | 3.40                 | 2.88                   | 1.86 $\pm$ 0.07<br>2.22 $\pm$ 0.06 |
| [S IX]/Pa $\beta$     | 0.0                  | 0.0                  | 0.0                    | 0.10 $\pm$ 0.02<br>...             |
| [Fe II]/Pa $\beta$    | 0.53                 | 0.80                 | 0.64                   | 0.40 $\pm$ 0.04<br>0.9 $\pm$ 0.09  |
| [Si VI]/Br $\gamma$   | 1.30                 | 0.50                 | 0.98                   | 2.41 $\pm$ 0.24<br>1.09 $\pm$ 0.17 |
| [Si VII]/Br $\gamma$  | 0.10                 | 0.0                  | 0.06                   | 3.00 $\pm$ 0.29<br>1.09 $\pm$ 0.17 |
| [Ca VIII]/Br $\gamma$ | 0.0                  | 0.0                  | 0.0                    | 0.35 $\pm$ 0.08<br>...             |
| [Si VII]/[Si VI]      | 0.09                 | 0.0                  | 0.06                   | 1.24 $\pm$ 0.07<br>1.0 $\pm$ 0.1   |
| [S IX]/[S VIII]       | 0.0                  | 0.0                  | 0.0                    | 0.39 $\pm$ 0.08<br>...             |
| [Ca VIII]/[Si VII]    | 0.0                  | 0.0                  | 0.0                    | 0.11 $\pm$ 0.01<br>...             |

Notes. <sup>a</sup> $U = -1.66$ ;  $R = 221$  pc;  $n_{\text{H}} = 500$  cm<sup>-3</sup>.

<sup>b</sup> $U = -1.96$ ;  $R = 221$  pc;  $n_{\text{H}} = 10^3$  cm<sup>-3</sup>.

<sup>c</sup>60 per cent cloud A, 40 per cent cloud B.

<sup>d</sup>Only [Si VII], [Si VI] and [S IX] are detected to the SW at this position. For that reason, only [Si VII]/[Si VI] is shown.

<sup>e</sup>The first entry corresponds to the NE aperture while the second one to the SW aperture.

<sup>f</sup>Dereddened;  $E(B - V)_{\text{NE}} = 0.41 \pm 0.09$ ;  $E(B - V)_{\text{SW}} = 0.8 \pm 0.3$ ;  $\text{Pa}\beta_{\text{NE}} = 2.90 \pm 0.07 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>;  $\text{Pa}\beta_{\text{SW}} = 4.31 \pm 0.05 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

the main input parameters. Other parameters include the pre-shock density,  $n_0$ , and the pre-shock magnetic field,  $B_0$ .

Tables 1–12 of CV01 show that shock-dominated clouds ( $F_{\text{h}} = 0$ ) with shock velocities in the range 300–1500 km s<sup>-1</sup> strongly favour the production of CLs. They predict [Si VII]/[Si VI] ratios between 1.5 and 3 and  $0.4 < [\text{S IX}]/[\text{S VIII}] < 1$  (models 56 and 70 for example). For all these clouds, solar metallicity,  $n_0 = 300$  cm<sup>-3</sup> and  $B_0 = 10^{-4}$  G were adopted. When coupled to the presence of the radiation field from the central source (e.g.  $\log F_{\text{h}} = 12$ , model 62), the values of these two ratios ( $\sim 0.8$  and  $\sim 0.1$ , respectively) are still consistent with our observations.

Other models which consider the effects of shocks provide additional support to the above results. Allen et al. (2008) published a library of fully radiative shock models which include both the radiative shock and its photoionized precursor. Similar to the models of CV01, the shock velocity, the pre-shock density and the intensity of the magnetic field are the main input parameters. Model predictions for the composite shock+precursor structure for the [Si VII]/[Si VI] ratio are found to vary from 0.5 to 1.2 for velocities between 500 and 1000 km s<sup>-1</sup>, respectively, and  $n_0$  of 100 cm<sup>-3</sup>. The shock velocities are significantly higher than those found by Ciroi et al. (2003) in their modelling of the optical spectra of the SW cone of NGC 4388. Composite models which account for the combined effects of photoionization and shocks were able to reproduce the

**Table 9.** CL ratios from model and observations at 276 pc NE and SW of the AGN.

| Line ratio           | Cloud A <sup>a</sup> | Cloud B <sup>b</sup> | Composite <sup>c</sup> | Observed <sup>d,e,f</sup>          |
|----------------------|----------------------|----------------------|------------------------|------------------------------------|
| [S III]/Pa $\beta$   | 6.61                 | 8.81                 | 7.05                   | 6.73 $\pm$ 0.15<br>6.64 $\pm$ 0.32 |
| [S VIII]/Pa $\beta$  | 0.0                  | 0.0                  | 0.00                   | 0.15 $\pm$ 0.04<br>...             |
| [S II]/Pa $\beta$    | 0.13                 | 0.23                 | 0.15                   | 0.28 $\pm$ 0.06<br>...             |
| He I/Pa $\beta$      | 2.4                  | 3.23                 | 2.57                   | 1.72 $\pm$ 0.04<br>2.15 $\pm$ 0.12 |
| [Fe II]/Pa $\beta$   | 0.74                 | 1.16                 | 0.82                   | 0.44 $\pm$ 0.02<br>1.28 $\pm$ 0.16 |
| [Si VI]/Br $\gamma$  | 0.72                 | 0.2                  | 0.62                   | 1.69 $\pm$ 0.4<br>0.97 $\pm$ 0.2   |
| [Si VII]/Br $\gamma$ | 0.04                 | 0.0                  | 0.03                   | 2.6 $\pm$ 1.1<br>1.6 $\pm$ 0.3     |
| [Si VII]/[Si VI]     | 0.06                 | 0.0                  | 0.05                   | 1.5 $\pm$ 0.51<br>1.6 $\pm$ 0.4    |

<sup>a</sup> $U = -2.16$ ;  $R = 276$  pc;  $n_{\text{H}} = 500$  cm<sup>-3</sup>.

<sup>b</sup> $U = -1.96$ ;  $R = 276$  pc;  $n_{\text{H}} = 10^3$  cm<sup>-3</sup>.

<sup>c</sup>80 per cent cloud A, 20 per cent cloud B.

<sup>d</sup>[S VII], [Si VI] and [S VIII] are the only CLs detected at this position. Thus, only line ratios involving these lines are shown.

<sup>e</sup>The first entry corresponds to the NE aperture while the second one to the SW aperture.

<sup>f</sup>Dereddened;  $E(B - V)_{\text{NE}} = 0.41 \pm 0.09$ ;  $E(B - V)_{\text{SW}} = 0.8 \pm 0.3$ ;  $\text{Pa}\beta_{\text{NE}} = 1.07 \pm 0.02 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>;  $\text{Pa}\beta_{\text{SW}} = 1.09 \pm 0.05 \times 10^{-15}$  erg cm<sup>-2</sup> s<sup>-1</sup>.

observed, high [O III]  $\lambda 5007/\text{H}\beta$  ratio, marginally consistent with simple photoionization.

The alignment between radio jets and the morphology of the ionized gas has also been observed in other Seyfert galaxies by means of 3D IFU observations (Müller-Sánchez et al. 2011; Mazzalay et al. 2013; Riffel et al. 2015a,b). One example is NGC 1068, well known for displaying a prominent radio jet in the nuclear and circumnuclear region, with most of the NLR ionized gas following the morphology and structure of the radio emission (Axon et al. 1998; Exposito et al. 2011; Mazzalay et al. 2013). Geballe et al. (2009) had already found enhanced CL emission where the radio jet changes direction, while Mazzalay et al. (2013) showed the necessity of shocks to reproduce the enhanced CL ratios as far as 150 pc from the AGN. The case for NGC 4388 is not much different. The observed coronal emission follows that of the radio jet, as observed here from our data and from Greene et al. (2014). Moreover, outflowing ionized gas has been systematically reported in this object. For the data presented here, evidence of outflowing gas is easily seen in Fig. 10, when the disc rotation is subtracted from the observed velocity radial velocity measured in the CLs. Blueshifted gas is clearly seen in the NE while redshifted gas is detected towards the SW. The outflowing component is the largest for the high-ionization lines and enhances towards the SW, where the extinction is significantly reduced.

We should keep in mind, though, that the shock model coupled to radiation from the central source predictions provides us with only a first-order approximation. In order to have a full description of the CLR based on model fitting, we should suitably combine clouds under different physical conditions (i.e. clouds with different  $V_s$  and  $n_0$ ) with the proper weight so that the emission lines and the observed continuum can be reproduced (Contini, Prieto & Viegas 1998; Contini, Rodríguez-Ardila & Viegas 2003; Rodríguez-Ardila, Contini & Viegas 2005). This is far beyond the scope of this paper

and is left for a future publication. What is most important here is that we have collected solid evidence of the necessity of shocks coupled to photoionization by the AGN in order to reproduce CL flux ratios at distances as far as a few hundred parsecs, where photoionization by the central source predicts no or very faint CL emission. Unrealistic physical conditions need to be assumed for the gas if we want to explain the observed high-ionization lines in terms of only one mechanism.

## 6 CONCLUDING REMARKS

We have carried out the first spectroscopic analysis of the nuclear and circumnuclear region of the Seyfert 2 galaxy NGC 4388 covering simultaneously the wavelength interval 0.84–2.45  $\mu\text{m}$ , part of it never being reported in the literature. The lower sensitivity of NIR to dust allowed us to unveil the north-east region of this source, traditionally hidden at optical wavelengths, in detail and using a wide variety of emission lines both of low and high ionization.

Our data reveal that NGC 4388 displays an outstanding emission-line spectrum with prominent lines of [S III]  $\lambda\lambda 9068, 9531 \text{ \AA}$ , He I 1.083  $\mu\text{m}$ , [Fe II] 1.257  $\mu\text{m}$ , Pa $\beta$ , H<sub>2</sub> 2.122  $\mu\text{m}$ , [Si VI] 1.963  $\mu\text{m}$  and [Si VII] 2.48  $\mu\text{m}$ . They all extend from the nucleus to the NE and SW ends of the slit. Along the spatial direction, the NLR gas has a complex, irregular structure, with at least two knots of emission, with the brightest one coinciding with the peak of the continuum light distribution. The asymmetry of the light profile distributions, with excess emission towards the SW compared with the NE, is most pronounced at shorter wavelengths. Some of the structures detected are seen at the first time in our data.

We determined the average extinction for the inner 560 pc of NGC 4388 from both the H I and [Fe II] lines. The results confirm that the central regions of NGC 4388 are dusty, with the dust distributed inhomogeneously, peaking at the nucleus with an  $E(B - V)$  of  $1.81 \pm 0.3$  mag. It then decreases both to the NE and SW, although it remains high mainly to the NE, consistent with the fact that this inner region is seen through the galaxy disc. To the SW at 220 pc from the nucleus, we see a highly dusty region with  $E(B - V)$  reaching  $0.8 \pm 0.3$  mag.

The emission-line ratios [S III]/Pa $\beta$ , [Si VI]/Br $\gamma$  and [Si VII]/Br $\gamma$  show that in the inner 500 pc of NGC 4388 the gas distribution is highly inhomogeneous, with at least two regions of enhanced high-ionization emission lines: one in the centre, and another at  $\sim 250$  pc NE of the nucleus. A third peak of enhanced ionization is observed to the SW, and is evident in the [S III]/Pa $\beta$  and [Fe II]/Pa $\beta$  line ratios. The enhancement in ionization suggests strong interaction between the radio jet and the circumnuclear NLR gas.

We are able to analyse the gas kinematics based on several lines of moderate to very high excitation. The results show that there is a significant parcel of gas which is not rotation dominated and located out of the disc of the galaxy. High-ionization lines display flat PV curves, suggesting that the bulk of this emission consists of outflowing gas. Double-peaked [Fe II] lines SW of the nucleus give additional support to this picture. Only the molecular hydrogen and the stellar component follow a rotation pattern consistent with disc rotation.

The forbidden high-ionization line spectrum observed in NGC 4388 is outstanding, not only because of the strength of the emission lines but also because of the size of the emission region where it is detected. [Si VI] and [Si VII], for example, fill up the FOV covered by the slit, that is, nearly 600 pc along the spatial direction. Few AGNs in the literature are reported to display such a large CLR. These observations cannot be explained solely as due

to photoionization by radiation from the central engine. Models which consider only this excitation mechanism fail at reproducing off-nuclear line ratios. Therefore, an additional source of gas excitation must be present. Models which include the effects of shocks coupled to photoionization by the central source are able to account for the observations. This result is supported by observational evidence which suggests interactions between the radio jet and the ISM in the central few hundred parsecs of this AGN.

The picture which emerges from our observations highlights the very complex nature of the nuclear and circumnuclear region of NGC 4388. This AGN is one of the best pieces of evidence of the intricate mixture of an AGN, a radio jet, dust and a rich ISM. Determining the precise contribution of each of these components to the observed spectrum would require observations at superior angular resolution as provided by AO and sub-arcsecond observations of the radio jet with VLA.

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