

# Searching for evidence of jet–cloud interaction in radio galaxies. First results for 3C 381

V. Reynaldi<sup>1,2★</sup> and C. Feinstein<sup>1,2†‡</sup>

<sup>1</sup>*Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Paseo del Bosque s/n, La Plata 1900, Argentina*

<sup>2</sup>*Instituto de Astrofísica de La Plata, CONICET, Argentina*

Accepted 2013 January 7. Received 2012 December 5; in original form 2012 October 18

## ABSTRACT

We present results of Gemini spectroscopy and *Hubble Space Telescope* imaging of the 3C 381 radio galaxy. Possible ionizing mechanisms for the extended emission-line region were studied through state-of-the-art diagnostic analysis employing line ratios. Photoionization from the central engine as well as mixed medium photoionization models fail in reproducing both the strengths and the behaviour of the highest excitation lines, such as [Ne v] $\lambda$ 3424, He II and [O III] $\lambda$ 5007, which are measured at very large distances from the active galactic nucleus. Shock–ionization models provide a better fit to the observation. Expanding shocks with velocities higher than 500 km s<sup>−1</sup> are capable of reaching the observed intensity ratios for lines with different ionization states and excitation degrees. This model also provides a direct explanation of the mechanical energy input needed to explain the high-velocity line-splitting observed in the velocity field.

**Key words:** galaxies: active – galaxies: individual: 3C 381 – intergalactic medium – galaxies: jets – galaxies: structure.

## 1 INTRODUCTION

One of the most striking features found in radio galaxies (RG) has been the presence of large regions of ionized gas not only confined to central regions but also extending from tens to hundreds of parsecs from the host galaxies (Fosbury 1989; McCarthy 1993; Binette, Wilson & Storchi-Bergmann 1996; Solórzano-Iñarrea, Tadhunter & Axon 2001). These extended emission-line regions (EELR)<sup>1</sup> received their name for being located towards the outskirts of the galaxies, and far beyond the narrow-line region (NLR), which is closer to the active galactic nucleus (AGN; Peterson 1997). However, while the NLR has shown itself as a direct consequence of the

nuclear activity (Peterson 1997, and references therein), the origin of the EELR's gas and the mechanisms that trigger its emission are still subject of debate (Solórzano-Iñarrea, Tadhunter & Bland-Hawtorn 2002).

These EELRs are characterized by emission of narrow forbidden lines of several species with a variety of ionization states and excitation degrees, together with strong hydrogen recombination lines (McCarthy 1993; Peterson 1997). Also, the shapes, intensities and morphology of this gas vary from object to object.

There already exist studies that could give some clues to the physics involved in the emission of these large regions. For example, McCarthy et al. (1987) and Chambers, Miley & van Breugel (1987) showed that the ultraviolet (UV) continua of powerful radio sources at  $z > 0.6$  are closely aligned with their radio sources. For lower redshifts and lower luminosity radio galaxies, alignments of the extended emission-line gas with the radio structures were also found (see Baum & Heckman 1989). One possible explanation for these observations is that if it is assumed that the EELRs could be bright, large and unresolved from the host galaxy, the optical shape of the object would be dominated by the EELR in the case of optically poor spatially resolved radio galaxies. So, this is a strong indication that the radio jet could be the triggering mechanism for the ionization of these regions.

With the higher resolution instruments, several studies were carried out with the aim of understanding what kind of mechanisms can modify the physical condition of the kiloparsec-scale interstellar medium or intergalactic medium (IGM). Specifically, any ionizing

★E-mail: vreyaldi@fcaglp.unlp.edu.ar

†Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation (NSF) on behalf of the Gemini partnership: the NSF (USA), the Science and Technology Facilities Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

‡Based on observations made with the NASA/ESA *Hubble Space Telescope*, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

<sup>1</sup> They are also known as extended narrow-line region when they are referred to Seyfert galaxies.

mechanism should be able to explain the emission of radiation in a place with no apparent local source of ionizing photons, where the stellar radiation could not account for the large amount of photons that are being observed. A very wide sample of objects, among them Seyfert and radio galaxies, have been imaged by *Hubble Space Telescope* (*HST*) and many of them show large amounts of highly ionized and disturbed gas on their outskirts.

Two important issues concerning these extended ionized regions remain uncertain and they are being discussed: their origin and the mechanisms involved in their ionization. We have started to investigate the latter using the most acceptable theories to date: photoionization, mixed matter (Binette et al. 1996, 1997) and shock-ionization (Dopita & Sutherland 1995, 1996; Allen et al. 2008; Groves & Allen 2010).

Photoionization assumes that the UV photon flux produced by the AGN ionizes the line-emitting gas; it is described by the dimensionless ionizing parameter  $U$ , which accounts for radiation field dilution as the distance from the nucleus increases. More complex photoionization models were performed by Binette et al. (1996, 1997) who introduced the presence of gas clouds with different optical depths, and different values for  $U$ . On the other hand, shock-ionization is triggered by shock waves driven by the radio jets. Those shock waves compress, heat and accelerate the IGM; thus causing it to produce emission. Dopita & Sutherland (1995, 1996) and later Allen et al. (2008) and Groves & Allen (2010) developed magnetohydrodynamic models for shock-ionization, for both low- and high-shock velocities. When high speeds are considered, a radiative precursor region is created in front of the shock wave by the most energetic photons. As a consequence, the emission region gets bigger (it is composed by the precursor and the hot shocked gas) and the spectrum shows a mixture of ionization and excitation states.

Both scenarios have been tested in a wide sample of active galaxies. Capetti et al. (1995a,b, 1996), Capetti, Axon & Macchetto (1997) and Winge et al. (1997) were the first to show that shock-ionization best explains the optical emission in the NLR in nearby Seyfert galaxies (Mrk 3, Mrk 6, Mrk 573, NGC 1068, NGC 4151 and NGC 7319). Recently, Rosario et al. (2010a,b) have shown that this mechanism also occurs in NGC 5929 and SDSS J1517+3353. In the case of powerful 3CR radio sources, Feinstein et al. (1999, 2002), Márquez et al. (2000), Solórzano-Iñarrea et al. (2001, 2002), Solórzano-Iñarrea & Tadhunter (2003), Tilak et al. (2005), Christensen et al. (2006) and Hardcastle, Massaro & Harris (2010) showed that this interaction can be found in the EELRs of 3C 299, 3C 244.1, 3C 171, 3C 34, 3C 330, 3C 352, 3C 435A, 3C 265, 3C 196, 3C 277.3, and also in PKS 2250–41. In contrast, Robinson et al. (2000) and Solórzano-Iñarrea et al. (2004) have proved that 3C 321 and the powerful radio galaxies 0850–206 and 1303+091 are photoionized by the AGN.

### 1.1 The galaxy 3C 381

3C 381 is a FR II double-lobed radio source. It has a flux density of 16.6 Jy at 178 MHz (Laing, Riley & Longair 1983). The radio structures are located in an approximate north-south direction (see figs 21 and 22 from Leahy & Perley 1991), the radio axis being defined by the line that connects the radio core with the two hotspots. 3C 381 is a large  $\sim 74$  arcsec radio source, the south lobe is larger than the north one (40.5 and 33.4 arcsec, respectively; Leahy & Perley 1991); its inner edge is more separated from the central source

**Table 1.** Log of *HST* observations.

Camera	Date	Exp. time	Filter name	Exposures
WFPC2	1995 February 11	140 s	F702W	2
	1995 August 13	300 s	FR533N33	2

than the north lobe is. Nonetheless, a fairly symmetric rotational pattern can be distinguished near the centre<sup>2</sup> despite the separation.

The galaxy was studied at optical wavelengths by McCarthy, Spinrad & van Breugel (1995), who showed the presence of extended [O III] $\lambda$ 5007 emission. They characterized the object as one with the largest high-ionization emission-line regions amongst the low-redshift ( $z = 0.1605$ ) 3CR sources, which was later confirmed by *HST*/Wide Field Planetary Camera 2 (WFPC2) data (Fig. 1). The optical and radio features are not aligned. However, near the centre both radio lobes are rotationally symmetric, distorted and misaligned with respect to the radio axis (defined by the passage of the jet) in the same way as the [O III] $\lambda$ 5007 extended emission is. Moreover, the north-west (NW) optical elongation reaches the south extreme of the north lobe (see fig. 54 from Privon et al. 2008), but there is also an additional much more extended [O III] $\lambda$ 5007 filament 25 arcsec to the north (fig. 5 from McCarthy et al. 1995) that seems to be either embedded in or superimposed on the north lobe, in a direction approximately coincidental with the radio axis. The galaxy was classified as a high-excitation Galaxy based on its strong nuclear spectrum and its [O III] $\lambda$ 5007 luminosity (Buttiglione et al. 2009, 2010).

As all galaxies in the 3CRR catalogue, 3C 381 is located away from the Galactic plane (Laing et al. 1983). The extinction is low enough ( $E_{(B-V)} = 0.053$  mag; NASA/IPAC Extragalactic Database) that the Galactic reddening correction is negligible. Throughout this paper, we assume  $H_0 = 73$  km s<sup>-1</sup> Mpc<sup>-1</sup>,  $\Omega_{\text{matter}} = 0.27$ ,  $\Omega_{\text{vacuum}} = 0.73$ . Hence, at a redshift of  $z = 0.1605$ , 3C 381 is at a distance of 768 Mpc with a projected linear scale of 3.2 kpc arcsec<sup>-1</sup>.

We are going to investigate the emission coming from the EELR of 3C 381 by using long-slit Gemini Multi-Object Spectrograph (GMOS)/Gemini spectroscopy with the aim of determining which of the ionizing mechanisms mentioned above best explain the ionization state of this large-scale gas.

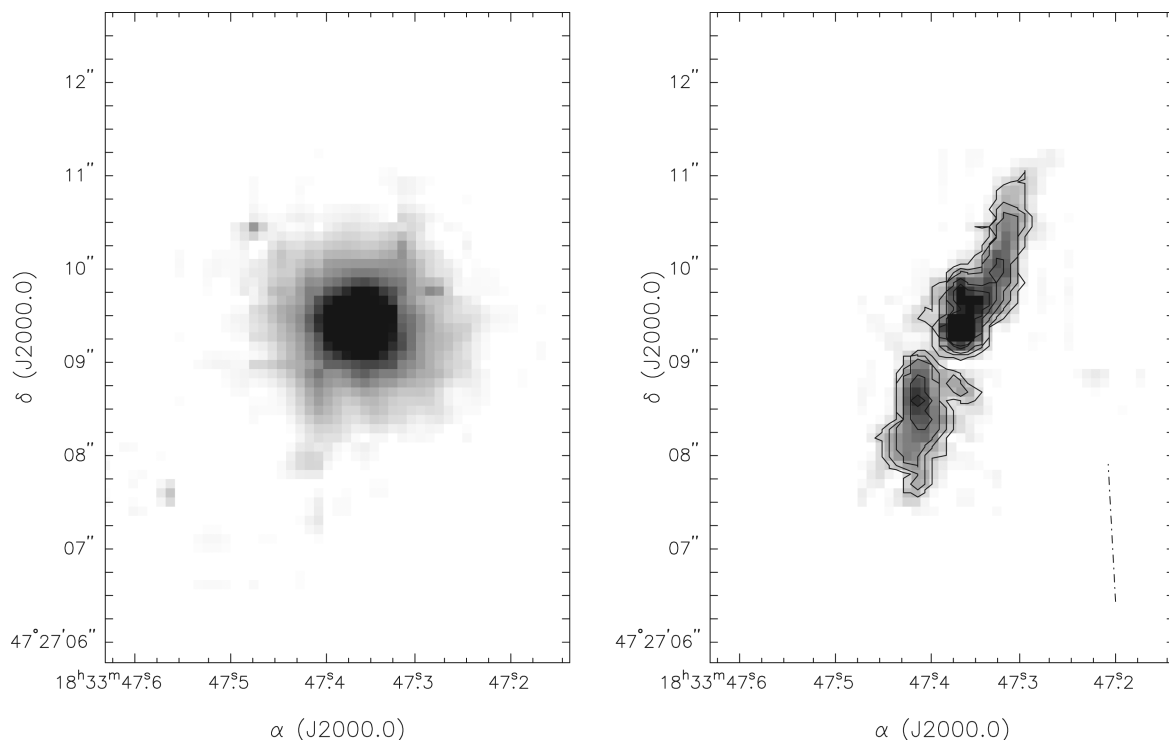
## 2 OBSERVATIONS

### 2.1 *HST*/WFPC2 imaging

3C 381 radio galaxy was observed with *HST*/WFPC2 as part of the 3CR Snapshot Survey (PI: Sparks). The log of observations is summarized in Table 1. Two broad-band F702W images were taken in 1995 February (140 s each one) which account for continuum emission from the host galaxy. Other two narrow-band ramp filter FR533N33 (300 s) images were taken in 1995 August. This filter was employed to find ionized gas surrounding the galaxy. The WFPC2 scales are 0.0455 arcsec px<sup>-1</sup> (146 pc px<sup>-1</sup>) for PC mode and 0.0996 arcsec px<sup>-1</sup> (319 pc px<sup>-1</sup>) for WF mode.

The F702W filter is close to Cousins'  $R$ ; these images were reduced as described in Martel et al. (1999) and then they were registered and added in order to produce one final image with higher

<sup>2</sup> See the DRAGNs website, <http://www.jb.man.ac.uk/atlas/>, which is maintained at the Jodrell Bank Observatory by J.P. Leahy, A.H. Bridle and R.G. Strom.



**Figure 1.** *HST*/WFPC2 images of 3C 381. Left: the stellar component accounting for the elliptical structure. Broad-band filter image. Right: [O III]λ5007-dominated image shown in grey-scale and contour map. The contours levels are 5, 7, 10, 18 and 22 per cent of the maximum intensity at the nucleus position. The radio axis direction (PA = 4°, de Koff et al. 1996) is also shown at the bottom-right of this panel.

signal-to-noise ratio (S/N). Data were reduced using the *STSDAS* package within *IRAF*, which includes the standard WFPC2 pipeline processing and cosmic ray removal. Given the redshift of the galaxy and its position on the CCD, the ramp filter produces an [O III]λ5007-dominated image (Fig. 1, right-hand panel). These structures are located at a position angle (PA) of 155°, they extend up to 2.2 arcsec to the NW and south-east (SE) from the nucleus, respectively, and they constitute the targets for our spectroscopic analysis.

As the *HST* images are flux calibrated data, photometry was done in order to calibrate the exposure time needed to have a good S/N for the spectroscopy. This procedure was performed by measuring the [O III]λ5007 emission and then its flux was scaled to the oxygen line in a quasar-like spectrum, which is the most similar template available. Both from the images and this analysis, it is clear that the nebular structures are very extended and they are bright enough to stand out over the stellar luminosity. However, our main interest is focused on the regions where the stellar component already vanishes, or it is so faint that there is no measurable contribution in the spectra.

## 2.2 GMOS spectroscopy

The long-slit spectrum was obtained in 2005 April using GMOS at the 8.1 m Gemini North telescope as part of the programme GN-2005A-Q-37 (PI: Feinstein; see Table 2 for the log of observations). The instrument was set up with a 0.5 arcsec width slit, and the

B600–G5303 grating  $R \sim 1700$  centred at about 4500 Å, which yields a resolution of  $0.9 \text{ Å px}^{-1}$ . Only one exposure of 2400 s was taken with  $2 \times 2$  binned CCD, implying a spatial resolution of  $0.1454 \text{ arcsec px}^{-1}$ . The slit was placed at a PA of 155°, along the optical–UV elongation.

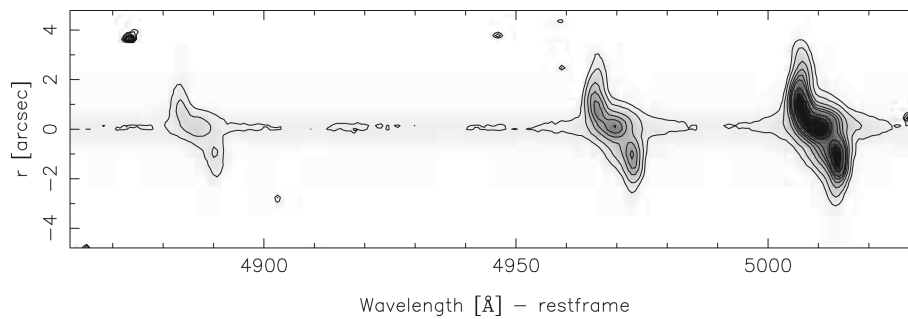
Data were reduced by using the *GEMINI-GMOS* package reduction tasks within *IRAF*. We followed the usual steps of bias subtraction, flat-field correction, wavelength calibration and sky subtraction. We performed cosmic ray rejection from the 2D spectrum by using two different tasks: *gscrrej* from *GEMINI* package and the Laplacian Cosmic Ray Identification (van Dokkum 2001), but we found some loss of information after the tasks were (separately) carried out. For these reasons, we decided not to apply this correction to our spectrum. However, the presence of a cosmic ray hit over a given profile in the extracted 1D spectrum is clearly detected because of its shape, intensity and width relative to the line itself, so cosmic ray contamination was easily removed from our measurements.

The spectrum covers  $\sim 2700 \text{ Å}$  in wavelength, from 3800 to 5800 Å. It includes emission lines of several species, from the bluest [Ne V]λ3424 to the reddest [O III]λ5007, the latter being the most important feature in the spectrum (Fig. 2). The set of identified lines is listed in Table 3, together with line fluxes relative to that of Hβ for each selected position. All the locations are referred to the galactic centre, which was morphologically determined both for the spectra and for the *HST* imaging. Since 3C 381 is an elliptical galaxy, and it is well fitted by a De Vaucouleurs profile, the centre can be determined very accurately for the *HST* continuum image. Concerning Gemini spectrum, the centre was located as the maximum intensity point within the stellar continuum. This point matches the maximum of the De Vaucouleurs profile.

Since Gemini spectrum has a resolution of  $0.1454 \text{ arcsec px}^{-1}$ , it gives a linear scale of about  $465 \text{ pc px}^{-1}$ , without projection

**Table 2.** Log of Gemini observation.

Instrument	Slit	Grating	Date	Exp. time
GMOS	0.5 arcsec	B600_G5303	2005 April 7	2400 s



**Figure 2.** 2D Gemini spectrum, from  $H\beta$  to  $[O\text{ III}]\lambda 5007$ . The ordinate scale indicates the SE (negative) and NW (positive). The contour levels are shown only to emphasize the grey-scale contrast.

**Table 3.** Set of identified emission lines in 3C 381 spectrum.

Line <sup>a</sup>	Flux 3.2 arcsec NW	Flux 1.6 arcsec NW	Flux GC <sup>b</sup>	Flux 1.6 arcsec SE	Flux 3.2 arcsec SE
$[\text{Ne III}]\lambda 3345$	–	0.18	0.47	–	–
$[\text{Ne V}]\lambda 3424$	–	0.81	1.05	0.57	–
$[\text{O II}]\lambda 3727$	9.93	4.28	2.58	3.01	4.91
$[\text{Ne III}]\lambda 3869$	–	1.47	1.19	1.16	–
$H\delta$ (4100)	–	0.22	0.19	0.19	–
$H\gamma$ (4340)	–	0.54	0.47	0.52	–
$[\text{O III}]\lambda 4363$	–	0.27	0.38	0.29	–
$\text{He II}$ (4686)	–	0.26	0.31	0.29	–
$[\text{Ar IV}]\lambda 4711^c$	–	0.04	–	0.11	–
$[\text{Ar IV}]\lambda 4740$	–	–	0.07	–	–
$H\beta$ (4861)	1	1	1	1	1
$[\text{O III}]\lambda 4959$	4.24	4.1	4.36	4.53	4.33
$[\text{O III}]\lambda 5007$	13.86	12.42	13.32	13.57	12.57

<sup>a</sup> Wavelengths in angstroms.

<sup>b</sup> Galactic Centre.

<sup>c</sup> Possible contamination from  $[\text{Ne IV}]\lambda 4718$ .

correction. Fig. 2 covers the range from  $H\beta$  to  $[\text{O III}]\lambda 5007$ ; the intensities of these lines are shown in grey-scale; the contours have been plotted with the aim of emphasizing the line's intrinsic shapes.

### 3 RESULTS

#### 3.1 *HST*/WFPC2 imaging

The galaxy shows a completely different morphology at broad-band compared with the narrow band. While the first shows the stellar component dominating the flux, the narrow-band filters are sensitive to the ionized gas. Its elliptical nature is clearly seen in broad-band filter (Fig. 1, left-hand panel). The elliptical structure is homogeneous and it is well fitted by a De Vaucouleurs ( $r^{1/4}$ ) surface brightness profile. It vanishes below the noise in the *HST* images at 1.7 arcsec from the nucleus, the stellar component being negligible as from this point.

On the other hand, the *HST*/WFPC2 ramp filter image shows the nebular emission dominated by  $[\text{O III}]\lambda 5007$ . These structures are elongated and they vanish in the outskirts of the host galaxy, giving a total extension from one end to the other of about 4.5 arcsec at a PA of  $155^\circ$  (counterclockwise from the North). The shapes of both features are quite different. The NW EELR is narrower than that of the SE; it has its maximal emission concentrated over its inner region from where it adopts an S shape towards its outer limit, reaching the south extreme of the northern radio lobe. The SE EELR, in contrast, is clearly detached from the central object.

The peak of its emission is located at 1.1 arcsec from the nucleus (Fig. 1, right-hand panel).

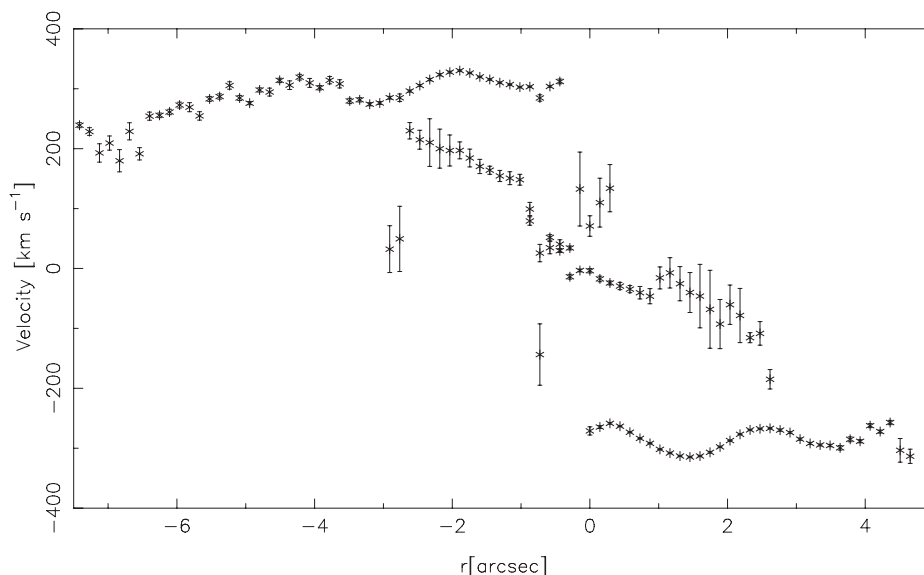
#### 3.2 GMOS spectroscopy

The high-excitation nature of 3C 381 established on the basis of its nuclear spectra is emphasized with our data, where high- and low-excitation lines coexist in a region that extends up to 3.2 arcsec (10 kpc) from the nucleus in each direction. However, the  $[\text{O III}]\lambda 5007$  emission is very intense, so it is measurable at a larger distance from the nucleus with a higher S/N than any other species. It extends up to 4.8 arcsec to the NW and 7.3 arcsec to the SE.

The angular size of the entire EELR measured by the  $[\text{O III}]\lambda 5007$  line reaches 12 arcsec (38.4 kpc), an extension of almost three times what the *HST* had detected, which indicates the existence of very low surface brightness structures towards the outer edges of the EELR.

The line shapes in the long-slit spectrum show a strong core over the central region, with a blueshifted wing to the NW and a redshifted wing to the SE (Fig. 2). Given the complexity of the lines, we have extracted one 1D spectrum for each spatial pixel across the slit to avoid the loss of spatial information. Once the extraction was performed, we found a complex spectral structure, where the line profiles can be decomposed into two or even three (in the case of  $[\text{O III}]\lambda\lambda 4959, 5007$ ) Gaussian components.

The Gaussian decomposition was performed by using the *ngauss-fit* task from the STSDAS package and the *splot* task from the NOAO



**Figure 3.** Velocity field computed from the components that form the  $[\text{O III}]\lambda 5007$  emission-line profile. As in Fig. 2, SE is plotted as negative coordinates and NW as positive.

package within *IRAF*. The total flux together with its rms error were obtained with *ngausfit* and then checked with *splot*. The *ngausfit* task works by iteration based upon a set of initial conditions on its three free parameters: central wavelength, intensity at the peak and full width at half-maximum (FWHM) for each component, in addition to the baseline continuum. We set initial conditions for the central wavelengths and line intensities; the FWHMs were left to converge by themselves. Finally, the initial values we proposed did not change significantly over the iterations and all the profiles reached their best fit with narrow ( $\text{FWHM} < 800 \text{ km s}^{-1}$ ) components for both forbidden and permitted lines. The line intensities decrease from the nucleus to the outskirts for the NW EELR, but there is a sudden increase towards the south-eastern region at around 1 arcsec ( $\sim 3.2 \text{ kpc}$ ). This behaviour was detected in the most intense lines as well as in the weakest ones. It reveals that the emission increase towards the SE in the  $[\text{O III}]\lambda 5007$  contour map (Fig. 1, right-hand panel) is common to the whole EELR SE gas.

Strong line-splitting was found not only in oxygen forbidden lines but also in hydrogen recombination lines. Although 3C 381 has been considered as a broad-line radio galaxy on the basis of a weak broad component in  $\text{H}\alpha$  (Grandi & Osterbrock 1978), no broad component was needed to construct the profile in any hydrogen line. Even when  $\text{H}\alpha$  lies outside the wavelength range we cover, we are able to say that 3C 381 has a Seyfert II-like spectrum. It has been confirmed not only by X-ray nuclear data taken with *Chandra* (Hardcastle, Evans & Croston 2009, and references therein), but also by recent optical nuclear data taken with Telescopio Nazionale Galileo (TNG; Buttiglione et al. 2009), which shows no evidence of such a broad component. For these reasons we assume that 3C 381 is a narrow-line radio galaxy, which is in keeping with its lack of a quasar-like core.

In addition to this line-splitting, the strongly distorted  $[\text{O III}]\lambda 5007$  emission-line profile also has a broad underlying component, mainly manifested inside the inner  $\pm 3 \text{ arcsec}$  ( $\pm 10 \text{ kpc}$ ). The broad wings in  $[\text{O III}]\lambda 5007$  (which are also detected in  $[\text{O III}]\lambda 4959$ ) make it necessary to use more than a single narrow Gaussian fit. The narrow component can be easily followed throughout the spectra, and its parameters are measured with high accuracy. On the other hand, the errors associated with the broad

component parameters are high, specially the FWHM. The measurement of this component is much more difficult than that of the narrower one, but its underlying presence is not arguable.

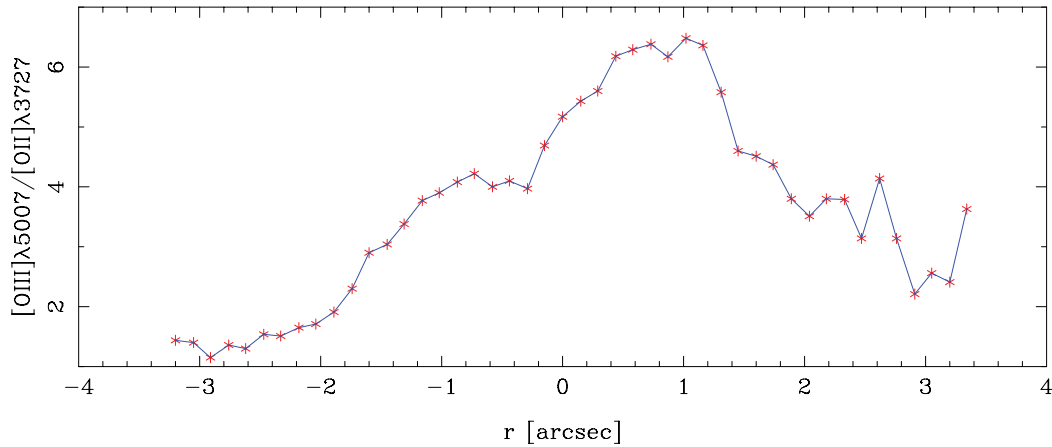
### 3.2.1 Kinematics of the emitting gas

Due to its brightness, the  $[\text{O III}]\lambda 5007$  emission line was used to compute the velocity field relative to the host galaxy systemic velocity (Fig. 3). A fairly symmetric distribution to each side of the nucleus is distinguished as an organized and collective pattern, coming from a gas component probably related to a disc. This rotation curve tends to stabilize around  $300 \text{ km s}^{-1}$  at  $\sim 1.5 \text{ arcsec}$  ( $\sim 5 \text{ kpc}$ ) from the galactic centre which is consistent with gravitational motion within the galactic potential (Tadhunter, Fosbury & Quinn 1989). However, there are also high-velocity components superimposed on that curve which follow neither ordered nor collective behaviour. Such a velocity shift cannot be explained under the gravitational hypothesis. The highest velocity components are located within the inner  $\pm 3 \text{ arcsec}$  ( $\pm 10 \text{ kpc}$ ); they are separated from the rotation curve by  $\pm 300 \text{ km s}^{-1}$  approximately. They deserve special attention because those disturbed kinematic components are also the broader ones (Fig. 3).

The high-velocity displacements among the kinematic components could be related to disturbing processes triggered by the radio-emitting components in different scenarios. Evidence of such processes has been found not only in radio galaxies where the radio components overlap the line-emitting gas, but also in radio sources where the radio structures are found far beyond the innermost EELR (Solórzano-Iñarrea et al. 2001). The same happens in 3C 381; the radio and optical features have different scales, accepting the outer edge of the NW EELR that reaches the south extreme of the northern lobe, in addition to the other ionized filament, detected in the same location of the north lobe (McCarthy et al. 1995). 3C 381 is one of these galaxies where the interaction between radio and optical features can be identified even when these components are not overlapped.

The kinematic disturbed components we find are strong indicators that this gas is undergoing a violent disturbing process, very





**Figure 4.** Spatial variation of the ionization parameter  $U$  expressed through the oxygen ratio (Penston et al. 1990). As in Fig. 2, SE is  $-$  and NW is  $+$ . Note that  $U$  does not follow the  $r^{-2}$  geometrical dilution but grows up at  $\sim 1$  arcsec towards the SE. Every emission line in 3C 381’s spectrum increases its intensity at the same location.

probably triggered by the radio structures. So, any modelling of the undergoing emission process must also account for the energy that is accelerating this component of gas.

#### 4 DISCUSSION

To understand and identify the main ionizing mechanism of the EELR, we test the line ratios from the 3C 381 spectrum with the results predicted from modelling of several mechanisms that could ionize the interstellar gas. In this process, we have to identify the main source of energy of the line emission, which could be the AGN (e.g. AGN photoionization, mixed matter models) or a local phenomena (e.g. shock-ionization). Most of these mechanisms are already modelled with predicted line ratios that can be easily contrasted with the observed data.

A direct way to model the problem of the ionizing photon budget is to calculate the dimensionless ionization parameter  $U$  through the empirical relationship (Penston et al. 1990) over the entire nebular region.

$$U = -2.74 - \log \left( \frac{[\text{O II}]\lambda 3727}{[\text{O III}]\lambda 5007} \right).$$

This is the simplest way to understand if the UV photons coming from the AGN could be responsible for these ionized regions of extended gas. This relation was obtained under the assumption of solar abundances and gas density of  $100 \text{ cm}^{-3}$ . It covers all possible configurations applicable to AGN, with spectral indices  $\alpha$  ( $\Phi_\nu \sim \nu^{+\alpha}$ ) varying in the range  $-2 < \alpha < -1$  and blackbody temperatures in the range  $10^5 \text{ K} < T < 2.1 \times 10^7 \text{ K}$ . The ionization parameter is used to find an estimation for the amount of ionizing photons emitted per time unit by the AGN ( $Q_0$ ), for which the ambient gas has to be known ( $Q_0 = U 4\pi r^2 c n_e$ ). Robinson, Tadhunter & Dyson (2002) performed long-slit spectroscopy and determined that at 1.4 kpc from the nucleus (PA =  $155^\circ$ ) the density has a value of  $370 \text{ cm}^{-3}$ .

We measured  $Q_0$  by using this local density together with  $U$  calculated in the same location where the density was obtained. At this point (1.4 kpc),  $U = 9.35 \times 10^{-2}$ . As our long-slit spectrum allows the spatial measurement of  $[\text{O II}]\lambda 3727$  and  $[\text{O III}]\lambda 5007$ , we can compute the line ratio and, under the assumptions of Penston’s relationship, trace the spatial evolution of  $U$  (Fig. 4). Even if the density changes as a function of position,  $Q_0$  is supposed to be

constant. So, we obtain  $Q_0 = 2.4 \times 10^{56} \text{ photons s}^{-1}$ . Both  $Q_0$  and  $U$  must be considered as minimum because the inclination is unknown, and it has not been corrected.

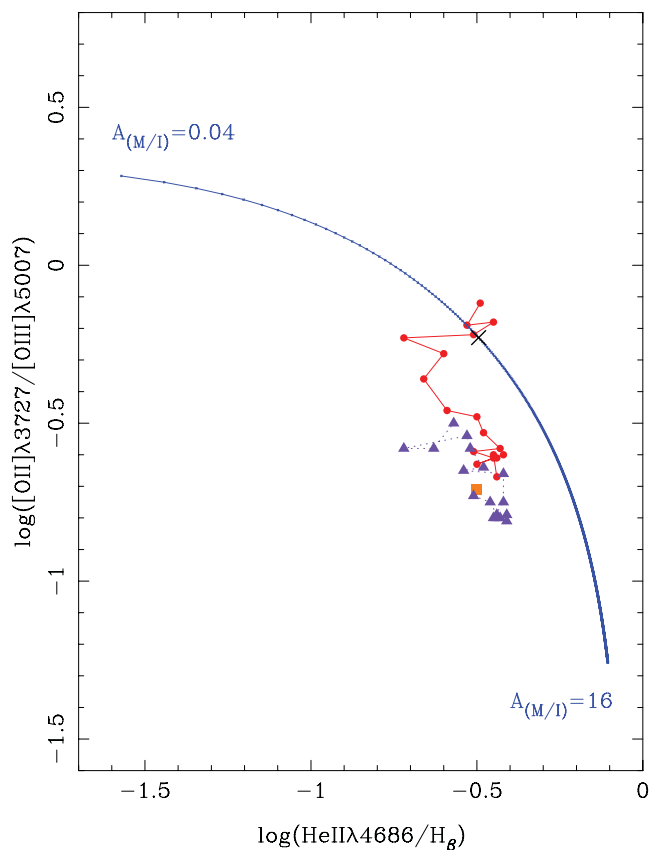
This  $Q_0$  is comparable to that of 3C 273, the most powerful radio loud quasar known at low redshift [ $Q_0 = 3.8 \times 10^{56} \text{ photons s}^{-1}$ ; Robinson et al. (2000)<sup>3</sup>]. Hardcastle et al. (2009) have shown that what they called X-ray ‘accretion related’ nuclear luminosity (absorption corrected) is a good indicator of the AGN power. The X-ray luminosity of 3C 381 is almost of an order of magnitude lower than that of quasars (see fig. 13 from Hardcastle et al. 2009) (and the  $[\text{O III}]\lambda 5007$  luminosity too). So it is very likely that the  $Q_0$  previously calculated is a very overestimated measurement of the ionizing power in 3C 381.

In addition, other problem arises concerning  $U$ . We expect that  $U$  evolves as  $U \sim n_e^{-1} r^{-2}$ . So it would be sensible to the geometrical dilution of the central ionizing radiation field, and the changes in the density. Fig. 4 reflects the behaviour of  $U$ , through  $[\text{O III}]\lambda 5007/[\text{O II}]\lambda 3727$ , under the assumptions of constant density (Penston et al. 1990). It can be clearly seen that  $U$  does not follow the  $r^{-2}$  dilution over a large distance. In contrast,  $U$  increases towards the south-eastern EELR and, even more, we must highlight that every emission line in the spectra increases its intensity towards the SE (at  $\sim 1$  arcsec). In order to produce such an increase in the emission (as  $U$  shows), the density should decrease faster than  $r^{-2}$  over a kiloparsec-scale distance, which seems to be unlikely. It is worth noting that the  $[\text{O III}]\lambda 5007/[\text{O II}]\lambda 3727$  line ratio will significantly change its predicted behaviour (with respect to the single ionizing source) if there is other off-nuclear source of ionizing photons, such as the *local* radiation field created by *local* radiative shocks. We will discuss it later.

Therefore, from the overestimated ionizing budget and the observed behaviour of the  $[\text{O III}]\lambda 5007$  and  $[\text{O II}]\lambda 3727$  line ratio, we think that it is very unlikely that a simple AGN photoionization could be the dominant ionizing mechanism.

Then, a more complex photoionization model is required. A clever approach was developed by Binette et al. (1996) doing a more sophisticated modelling of the way in which a clumpy medium absorbs the impinging radiation field. In this mixed matter model (Binette et al. 1996, 1997), the EELR is composed by two

<sup>3</sup> Their published value is  $Q_0 = 3 \times 10^{55} \text{ photons s}^{-1} \text{ ster}^{-1}$ .



**Figure 5.** Continuous line: mixed medium photoionization model from Binette et al. (1996). The black cross shows the position where  $A_{M/I} = 1$ . Its extreme values are shown at the end of the sequence. Each EELR was plotted separately, the data are connected to follow their trend with respect to the  $A_{M/I}$  sequence. The NW measurements were plotted as dots and those from the SE as triangles; the central spectrum is shown by a square.

different cloudy systems. The *matter-bounded* (MB) clouds, which are the optically thin lower density cloudlets, absorb a fraction of the incoming radiation. Since the highest energy photons are absorbed here, this is the place where the highest excitation lines are formed. The *ionization-bounded* (IB) clouds absorb the diluted ionizing field that exits the first component. The lowest excitation lines in the spectrum are formed in this optically thick cloudlets. In this clumpy system, the radiation field emitted by the central source is partially absorbed by the MB clouds, and once it has been leaked, it is completely absorbed by the IB clouds due to their higher density. The extension of the MB component is defined by the availability of  $\text{He}^+$  ionizing photons (Binette et al. 1996), which in turn are manifested by the presence of  $\text{He II}$  recombination lines (Osterbrock 1989).

However, the  $\text{He II}\lambda 4686$  emission 3C 381 extends up to 2.5 arcsec ( $\sim 8$  kpc) over each EELR, without the strong variation that the model proposes. The line intensity at the end of each EELR drops to  $\sim 10$  per cent of its maximum value at the galactic centre, while the intensity of  $[\text{O III}]\lambda 5007$ , the main feature in the spectrum, drops to less than  $\sim 5$  per cent of its maximum value in the same spatial extent. In fact, the extent to which the line is measured is in itself a problem, since it sets the spatial limit for the MB clouds. Consequently, there is no mixed material inside the inner 2.5 arcsec ( $\sim 8$  kpc); therefore, there applies again the hypothesis proposed by the simple AGN photoionization model discussed before, which fails in reproducing the scenario in 3C 381's environment.

The modelling is implemented by diagnostic diagrams parametrized by  $A_{M/I}$  (defined as the solid angle subtended by the MB clouds with respect to that of IB clouds) which varies as the  $\text{He II}/\text{H}\beta$  line ratio does. The diagram plotted in Fig. 5 uses the oxygen ratio  $[\text{O II}]\lambda 3727/[\text{O III}]\lambda 5007$  against  $\text{He II}/\text{H}\beta$ , which became an excitation axis given its relation with  $A_{M/I}$ . It is worthwhile comparing this diagram with fig. 7 from Binette et al. (1996) to ensure that the observed trend actually responds to changes in  $U$  rather than  $A_{M/I}$  (see also Ferruit et al. 1999 for the same kind of analysis on Mrk 573). Each EELR was plotted separately from the other, connecting the measurements to follow their trend with respect to the  $A_{M/I}$  sequence. The NW measurements were plotted as dots, and those from the SE as triangles; the central spectrum is shown by a square.

It is very unlikely that photoionization models could account for the whole observations. Even when there should be a contribution from photoionization, neither the observed increment in  $U$  towards the SE nor the line ratios can be reproduced by these kind of models.

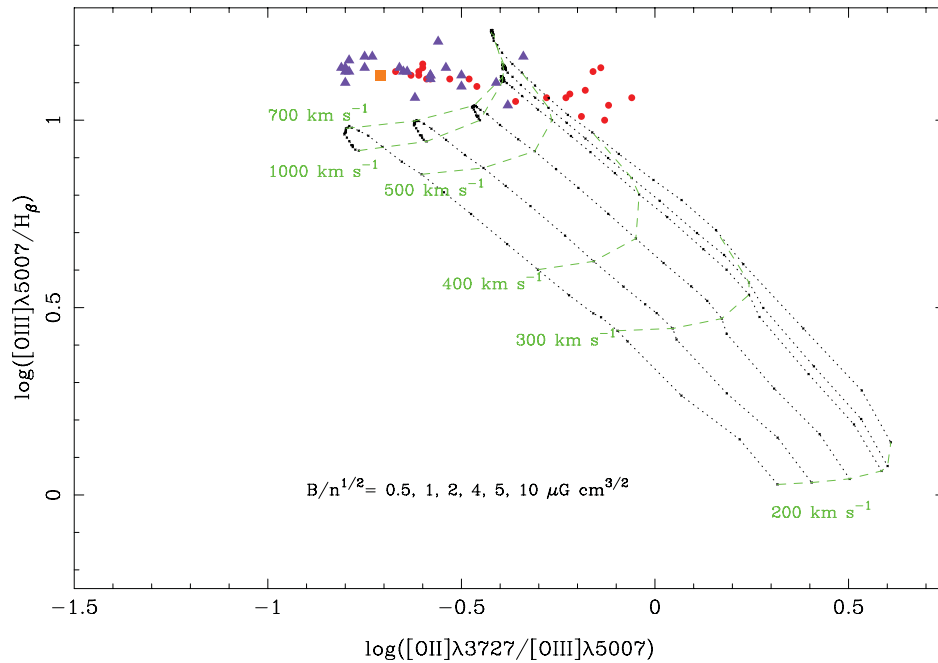
A plausible explanation for an increasing ionization parameter (note that  $U$  increases because  $[\text{O II}]\lambda 3727$  increases as well as  $[\text{O III}]\lambda 5007$  does) is the shock–ionization model, since either a local source of ionizing photons is needed or the AGN has improved its photoionizing power as a consequence of the disturbing processes undergone by the EELR material (Solórzano-Iñarra & Tadhunter 2003). This mechanism, also known as jet–cloud interaction, might provide a local ionizing field if the expanding shock waves are fast enough, but such a scenario should be manifested not only in line intensities but also in the kinematics of the region.

When a shock wave is capable of ionizing the medium where it propagates, the emission of radiation usually comes from the recombination region behind the shock front. But the fastest shocks ( $v > 170 \text{ km s}^{-1}$ ) create UV photons that can diffuse the jet both upstream and downstream, changing the ionization conditions of the entire region. Photons travelling upstream not only create an  $\text{H II}$ -like region (known as the precursor) ahead the shock, but also the post-shock gas is affected by photons travelling downstream. As a consequence, the line-emitting region gets an important contribution from the precursor: it is 10 to 20 per cent brighter than the shock in  $\text{H}\beta$  (Dopita & Sutherland 1995, 1996; Allen et al. 2008).

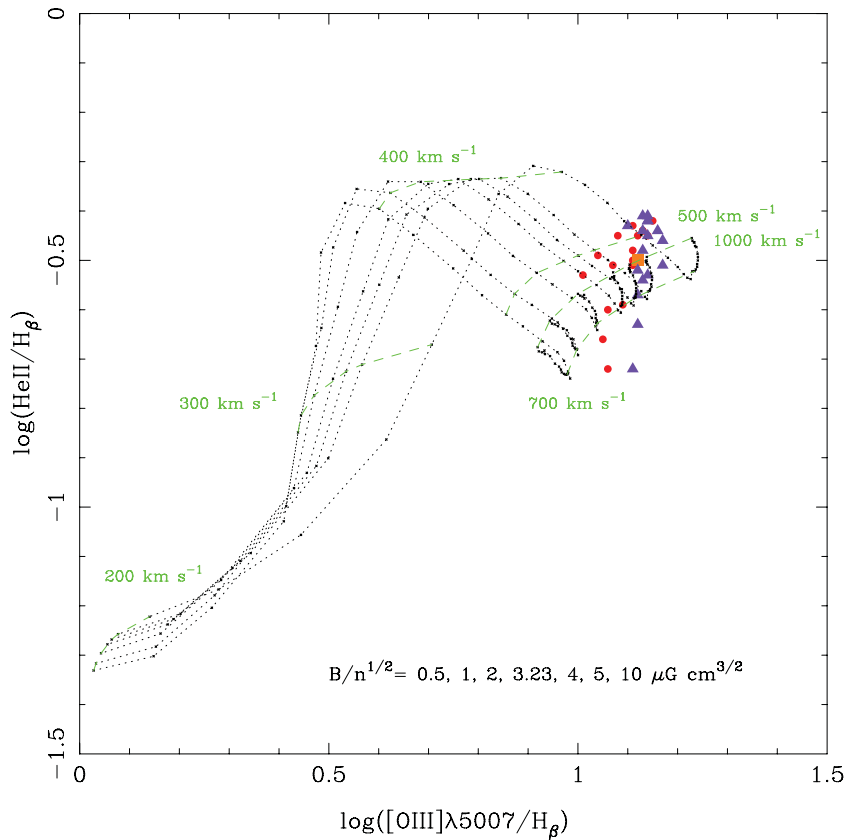
These models are also implemented through line ratio diagnostic diagrams. We have drawn (Figs 6–11) the shock+precursor grids (dotted lines, one line per magnetic parameter<sup>4</sup>) from the most recent modelling of these phenomena by Allen et al. (2008). Models with solar abundance and pre-shock gas density of  $100 \text{ cm}^{-3}$  were chosen. The only shock grids (no precursor) lie outside the range of our observations (compare the location of our data in Fig. 6 with fig. 1 from Dopita & Sutherland 1995, where both grids were plotted together). Shock velocities are also shown (dashed lines). Data are plotted as explained before.

We have used both  $[\text{O III}]\lambda 5007/\text{H}\beta$  and  $\text{He II}/\text{H}\beta$  as excitation axis. These ratios, as well as the other pairs of lines employed, are close in wavelength to minimize the unknown reddening effects. In other cases, we have used lines from the same species, to reduce the consequences that an unknown metallicity may have in our results (Baldwin, Phillips & Terlevich 1981). As a general characteristic, our  $[\text{O III}]\lambda 5007/\text{H}\beta$  and  $\text{He II}/\text{H}\beta$  values are higher than those predicted by the model. In addition, our  $[\text{O III}]\lambda 5007/\text{H}\beta$  measurements are also much more constant. Anyway, the fit is good despite these

<sup>4</sup> The magnetic parameter is defined as  $B/n^{1/2}$ ,  $B$  is the transverse magnetic field, and  $n$  is the pre-shock gas density (Dopita & Sutherland 1995).



**Figure 6.** Dotted lines: shock-ionization + precursor models from Allen et al. (2008), one line per magnetic parameter ( $B/n^{1/2}$ ) value. Shock velocities are drawn as dashed lines. See Fig. 5 for data reference.



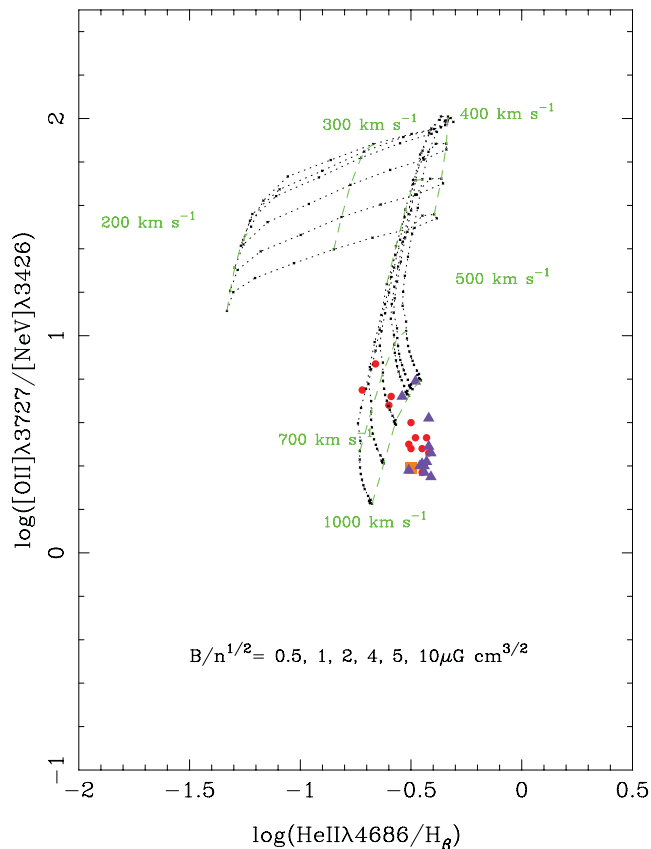
**Figure 7.** This plot shows the relation between two excitation axes,  $[O\text{ III}]\lambda 5007/H\beta$  and the other one implemented by Binette et al. (1996)  $\text{He II}/H\beta$ . See Fig. 6 for model references.

minor inconsistencies, and the best fit is reached in Fig. 7, which employs those line ratios.

The highly excited  $[\text{Ne V}]\lambda 3424$  emission line is used together with  $[O\text{ II}]\lambda 3727$  in the next two plots (Figs 8 and 9). The

$[\text{Ne V}]\lambda 3424$  emission extends up to  $\sim 5.5$  kpc away from the AGN; since  $\sim 95$  eV photons are needed to produce this emission line, it is very difficult for any photoionization model to explain such an extended emission (Komossa & Schulz 1997). In contrast, jet-cloud





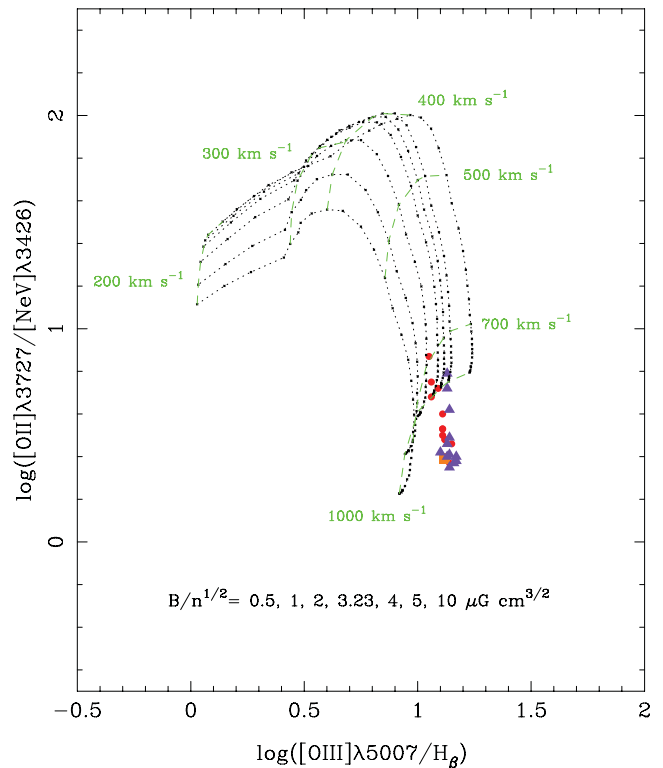
**Figure 8.** The high-excitation lines [Ne v]λ3424 and He II are combined with the lower excited [O II]λ3727 and Hβ. The shock-ionization models can reproduce the observations when the highest velocities are considered.

interaction may provide local energetic photons. As it is seen from the plots, these models also succeed in reproducing the relative intensity of [Ne v]λ3424 with respect to the lower excited [O II]λ3727 emission line.

The last two diagrams (Figs 10 and 11) use the temperature sensitive line ratio [O III]λ4363/[O III]λ5007, which is particularly complicated to be reproduced by any kind of model. Since the ‘temperature problem’ associated with this ratio (Dopita & Sutherland 1995) is widely known, we do not draw any conclusion based upon these plots, but we show them because, despite the fact of having poorer fits, the data behave as in previous diagrams.

Both high- and low-excitation emission lines are well fitted by the shock-ionization model, although there is a clear underprediction regarding [O III]λ5007 and He II. Furthermore, the extent to which the highest excited line in the spectrum is measured (i.e. [Ne v]λ3424) requires a budget of energetic photons that can be locally created by this kind of fast radiative shocks. In fact, the behaviour of the ionization parameter  $U$  is also explained by a local ionizing field. Data tend to be located over the fastest ( $500 < v < 1000 \text{ km s}^{-1}$ ) shocks with no exception. It is worth highlighting that the disturbed [O III]λ5007 components reported on the velocity field move with velocities in the same range as those predicted by the shock-ionization model. This is a strongly remarkable point since it is independent evidence to support the shock-ionization idea as the main source of the ionization of the gas.

Certainly, the most spectacular interaction between the radio jets and the IGM is observed at the edges of the lobes, where the shock waves driven by the jet give rise to the bright, highly overpressured

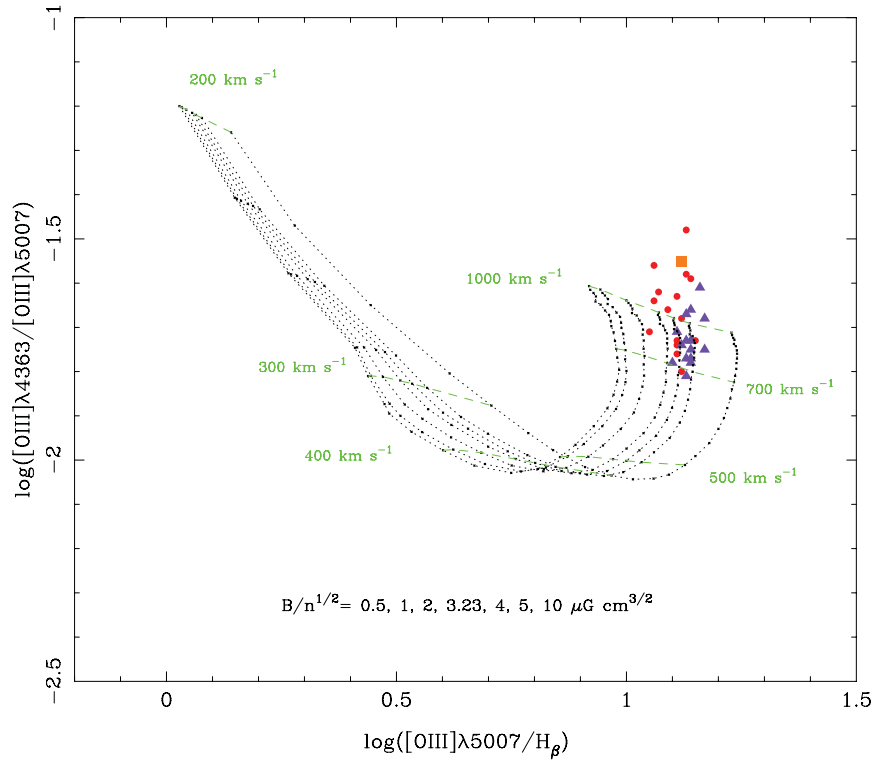


**Figure 9.** The same as Fig. 8 with [O III]λ5007/Hβ as the excitation axis. See Fig. 6 for model references.

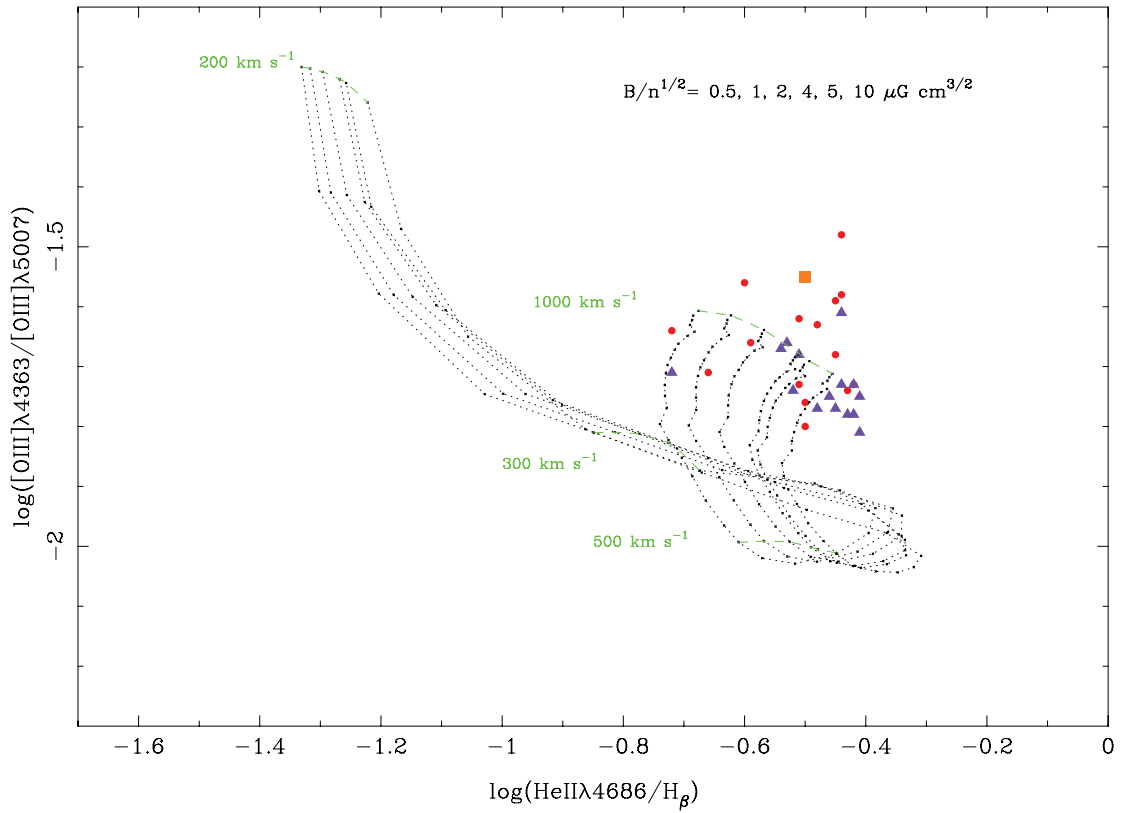
hotspots. The effects of shock waves in the way towards the hotspots have been also detected in the optical emitting gas. An impressive example of both jet–cloud and lobe–cloud interaction was reported in 3C 299 (Feinstein et al. 1999), where the EELR overlaps the radio lobe. However, a turning point was then achieved by Solórzano-Iñarra et al. (2001) who showed that, despite the large distance in-between the EELR and the radio lobes in their sample, the EELR’s gas undergoes jet-induced shock-related disturbing processes. In these latter cases, the key evidence came from the strongly disturbed kinematical patterns observed within the gas. The same kind of disturbing motion that we find in 3C 381.

Jet-driven shock waves are triggered near the AGN (near compared with the lobe scale) since the jet is supersonic in these regions (Leahy; [www.jb.man.ac.uk/atlas/dragns.html](http://www.jb.man.ac.uk/atlas/dragns.html)). Consequently, those shocks give raise to high-pressured regions within the clumpy EELR. Such a pressure excess was reported by Robinson et al. (2002). They made use of their density measurements (we have used it at the beginning of this section) to show that the EELR’s gas is overpressured with respect to the X-ray halo. They claimed that jet-induced shocks might be playing an important role in the region, but no kinematical argument was then available to support this scenario. The velocity field we have shown in Section 3.2.1 accounts for such an argument.

We have shown that the jet-driven shock-ionizing waves that are able to reproduce the observed line ratio are also those that move with velocities entirely compatible with the high-velocity line-splitting shown by the velocity field. So, the kinematics of the region, its ionization and also its pressure excess are now explained as consequences of the same process: the interaction of the radio jet with the IGM.



**Figure 10.** The temperature sensitive line ratio  $[\text{O III}]\lambda 4363/[\text{O III}]\lambda 5007$  against  $[\text{O III}]\lambda 5007/\text{H}\beta$ . Despite the *temperature problem*, the diagram shares the same characteristic of the previous plots. See Fig. 6 for model references.



**Figure 11.** The temperature sensitive line ratio  $[\text{O III}]\lambda 4363/[\text{O III}]\lambda 5007$  against  $\text{He II}\lambda 4686/\text{H}\beta$  as excitation axis. See Fig. 6 for model references.

## 5 CONCLUSIONS

From the study of the long-slit Gemini/GMOS spectra over the EELR found in the *HST* imaging of 3C 381 and the state-of-the-art modelling for the energetic balance for these structures, we find the following results.

- The nebular region extends up to 12 arcsec ( $\sim 38$  kpc) and it is larger than the stellar component as seen in the *HST* data, which vanishes below the noise at 1.7 arcsec ( $\sim 6$  kpc) from the nucleus.
- The kinematics of the EELR shows features of disturbing processes, where high-velocity gas components are clearly found not only near the central region but also towards the outskirts of the EELR. Differences up to  $600 \text{ km s}^{-1}$  in velocity are observed within the nebular structure.
- Line ratios have been used to compare theoretical predictions with our data and we found that the shock-ionization model with a precursor component predicts the observed line ratios. The fastest shocks ( $500 < v < 1000 \text{ km s}^{-1}$ ) are capable of reaching the extreme values of our data; there are variations amongst diagrams, but there is no contradiction between any line ratio.
- Shock-ionization models are likely to be the dominant ionizing process taking place within the EELR. In addition to the diagnostic diagrams that reproduce the observed line intensities with shock velocities coincident with what the velocity field shows, the local ionizing photons created by the shocks themselves provide a plausible explanation for both the existence of very extended high-excitation lines and the increment of  $U$  despite the increasing distance.

## ACKNOWLEDGEMENTS

We thank Dr M. Allen for sending us his modelling, which was very helpful for this paper. Also, we want to thank the Support Staff of the Gemini Observatory and the referee for his/her useful comments.

## REFERENCES

Allen M., Groves B., Dopita M., Sutherland R., Kewley L., 2008, *ApJS*, 178, 20  
 Baldwin J., Phillips M., Terlevich R., 1981, *PASP*, 93, 5  
 Baum S. A., Heckman T. M., 1989, *ApJ*, 336, 702  
 Binette L., Wilson A., Storchi-Bergmann T., 1996, *A&A*, 312, 365  
 Binette L., Wilson A., Raga A., Storchi-Bergmann T., 1997, *A&A*, 327, 909  
 Buttiglione S., Capetti A., Celotti A., Axon D., Chiaberge M., Macchetto F., Sparks W., 2009, *A&A*, 495, 1033  
 Buttiglione S., Capetti A., Celotti A., Axon D., Chiaberge M., Macchetto F., Sparks W., 2010, *A&A*, 509, A6  
 Capetti A., Macchetto F. D., Axon D. J., Sparks W. B., Boksenberg A., 1995a, *ApJ*, 448, 600  
 Capetti A., Axon D. J., Kukula M., Macchetto D. F., Pedlar A., Sparks W. B., Boksenberg A., 1995b, *ApJ*, 454, 85  
 Capetti A., Axon D. J., Macchetto F. D., Sparks W. B., Boksenberg A., 1996, *ApJ*, 469, 554

Capetti A., Axon D. J., Macchetto F. D., 1997, *ApJ*, 487, 560  
 Chambers K. C., Miley G. K., van Breugel W., 1987, *Nat*, 329, 60  
 Christensen L., Jahnke K., Wisotzki L., Sanchez S. F., Exter K., Roth M. M., 2006, *A&A*, 452, 869  
 de Koff S., Baum S., Sparks W., Biretta J., Golombek D., Macchetto F., McCarthy P., Miley G., 1996, *ApJS*, 107, 621  
 Dopita M., Sutherland R., 1995, *ApJ*, 455, 468  
 Dopita M., Sutherland R., 1996, *ApJ*, 102, 161  
 Feinstein C., Macchetto F. D., Martel A., Sparks W., McCarthy P., 1999, *ApJ*, 526, 623  
 Feinstein C., Macchetto F. D., Martel A., Sparks W., 2002, *ApJ*, 565, 125  
 Ferruit P., Wilson A., Falckle H., Simpson C., Pécontal E., Durret F., 1999, *MNRAS*, 309, 1  
 Fosbury R. A. E., 1989, in Meurs E. J. A., Fosbury R. A. E., eds, *ESO Workshop on Extranuclear Activity in Galaxies*. European Southern Observatory, Garching bei München, p. 169  
 Grandi S. A., Osterbrock D. E., 1978, *ApJ*, 220, 783  
 Groves B., Allen M., 2010, *New Astron.*, 15, 614  
 Hardcastle M., Evans D., Croston J., 2009, *MNRAS*, 396, 1929  
 Hardcastle M., Massaro F., Harris D., 2010, *MNRAS*, 401, 2697  
 Komossa S., Schulz H., 1997, *A&A*, 323, 31  
 Laing R. A., Riley J. M., Longair M. S., 1983, *MNRAS*, 204, 151  
 Leahy J. P., Perley R. A., 1991, *AJ*, 102, 537  
 Márquez I., Pécontal E., Durret F., Petitjean P., 2000, *A&A*, 361, 5  
 Martel A. et al., 1999, *ApJS*, 122, 81  
 McCarthy P., 1993, *ARA&A*, 31, 639  
 McCarthy P., van Breugel W., Spinrad H., Djorgovsky S., 1987, *ApJ*, 321, 29  
 McCarthy P., Spinrad H., van Breugel W., 1995, *ApJS*, 99, 27  
 Osterbrock D., 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*. University Science Books, Mill Valley, CA  
 Penston M. V. et al., 1990, *A&A*, 236, 53  
 Peterson B. M., 1997, *An Introduction to Active Galactic Nuclei*. Cambridge Univ. Press, Cambridge  
 Privon G., O'Dea C., Baum S., Axon D., Kharb P., Buchanan C., Sparks W., Chiaberge M., 2008, *ApJS*, 175, 423  
 Robinson T., Tadhunter C., Axon D., Robinson A., 2000, *MNRAS*, 317, 922  
 Robinson T., Tadhunter C., Dyson J., 2002, *MNRAS*, 331, 13  
 Rosario D., Whittle M., Nelson C., Wilson A., 2010a, *ApJ*, 711, 94  
 Rosario D., Shields G., Taylor G., Salvander S., Smith K., 2010b, *ApJ*, 716, 131  
 Solórzano-Iñarrea C., Tadhunter C., 2003, *MNRAS*, 340, 705  
 Solórzano-Iñarrea C., Tadhunter C., Axon D., 2001, *MNRAS*, 323, 965  
 Solórzano-Iñarrea C., Tadhunter C., Bland-Hawthorn J., 2002, *MNRAS*, 331, 673  
 Solórzano-Iñarrea C., Best P. N., Röttgering H., Cimatti A., 2004, *MNRAS*, 351, 997  
 Tadhunter C., Fosbury R., Quinn P., 1989, *MNRAS*, 240, 225  
 Tilak A., O'Dea C., Tadhunter C., Wills K., Morganti R., Baum S., Koekemoer A., Dallacasa D., 2005, *AJ*, 130, 2513  
 van Dokkum P., 2001, *PASP*, 113, 1420  
 Winge C., Axon D. J., Macchetto F. D., Capetti A., 1997, *ApJ*, 487, 121

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.