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# The extended emission line region of the Seyfert galaxy Markarian 573 [1]

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## ABSTRACT

We present the results of observations of the extended emission-line region of the Seyfert 2 galaxy Mrk 573, obtained using the WFPC2 camera on board HST and the TIGER integral field spectrograph on the Canada France Hawaii Telescope. The WFPC2 observations consist of a set of narrow-band linear ramp filter images in the [O III]$\lambda$5007 and H$\alpha$ + [N II]$\lambda$6583 lines, as well as continuum and other emission-line images obtained from the HST archive. The TIGER 3D (x,y,$\lambda$) data cubes cover the wavelength regions 5000/400 Å (central wavelength/range of wavelength), including H$\beta$ and [O III]$\lambda\lambda$4959,5007, and 6750/400 Å including H$\alpha$, [N II]$\lambda\lambda$6548,6583 and [S II]$\lambda\lambda$6717,6731. We describe and use a new deconvolution technique in which the spatial resolution of the TIGER data cubes is improved by using the higher resolution HST images in the same emission-lines, in combination with a standard Richardson-Lucy deconvolution. This 'guided' deconvolution allows us to obtain the [O III] gaseous kinematics with unprecedented spatial resolution of $\sim$0$''$.35.

The HST images outline the detailed complex structure of the central $\sim$3 kpc of this galaxy in the [O III] and H$\alpha$+[N II] lines, with strings of knots and a system of arcs straddling the nucleus. The [O III]/(H$\alpha$+[N II]) line ratio map shows that, taken together, all these individual features define a double wedge form with sharp edges, consistent with an ionization cone. The

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'linear' radio structure is closely associated with the strings of emission-line knots, with the northwest radio lobe lying inside one of the arcs. Strong velocity perturbations are found in the vicinity of all of the radio components, witnessing the interaction between the radio ejecta and the ambient material.

The spectral and kinematical properties of the different components of the emission-line region of Mrk 573 are discussed in terms of various models of the interaction between the ejecta and the ambient gas. The emission-line knots, associated with the radio knots and the velocity perturbations, probably trace the deflection of the radio jet by clouds. The inner arcs, $1''.8$ (570 pc) and $2''.3$ (720 pc) from the nucleus, may represent radiative bow shocks driven by the radio jets. The similar structure of each of these arcs in the different emission lines, and the absence of any strong kinematic perturbation at the arcs themselves, indicate that they are not 'photoionizing shocks', in which the gas is ionized by radiation from the radiative shock itself. Instead, the arcs are photoionized by an external source of radiation. The outer arcs, $2''.9$ (0.9 kpc) and $3''.6$ (1.1 kpc) from the nucleus, mark the transition between the narrow line and extended narrow line regions of Mrk 573. As in the case of the inner arcs, photoionizing shocks are ruled out on the basis of their optical emission-line properties. We use the measured variation of the ionization parameter and gas density to derive the flux of ionizing photons as a function of distance from the nucleus. We find that, unless the ionizing photons flux of the compact central source has decreased by a factor ten over the last 4000 years, a model in which all the ionizing photons originate in the central source is excluded. Instead, we speculate that, if the central ionizing source has not varied, fast shocks, possibly associated with the jet/cloud interactions, may provide the required spatially extended source of ionizing photons.

*Subject headings:* galaxies: active — galaxies: individual (Mrk 573) — galaxies : kinematics and dynamics — galaxies: jets — galaxies: nuclei — galaxies: Seyfert

## 1. Introduction

Study of the narrow line region (NLR) and extended narrow line region (ENLR) of Seyfert galaxies, in particular their relationship to the ionizing nuclear radiation, is a powerful tool to probe the inner structure of active galaxy nuclei (AGN). The existence of 'ionization cones' in a number of Seyfert galaxies (e.g. Wilson & Tsvetanov 1994) and arguments that the ionized gas in Seyfert 2 galaxies is illuminated by more ionizing photons than are radiated toward Earth (e.g. Kinney et al. 1991), have strongly supported the idea that the nuclear ionizing radiation is collimated, as expected in the so-called 'unified model' for AGN (see reviews by Antonucci 1993; Osterbrock 1993; Urry & Padovani 1995).

However, even if this simple picture holds for the ENLR (see e.g. Unger et al. 1987), the close morphological (Haniff, Wilson & Ward 1988; Capetti et al. 1996; Falcke et al. 1996; Falcke, Wilson & Simpson 1998) and kinematical (e.g. Whittle et al. 1988; Pécontal et al. 1997) association between the NLR gas and the radio-emitting material suggests a more complicated picture, in which interaction between the radio ejecta and the ambient gas plays a significant role in the energy budget of the NLR, as first proposed by Wilson & Willis (1980). The isolated Seyfert 2 galaxy Mrk 573 stands as a good example of this dichotomy between the NLR and the ENLR, and of the complexities resulting from the presence of both collimated ionizing radiation and an interaction between the radio ejecta and ambient gas.

In narrow-band emission-line imaging, Mrk 573 exhibits a structure suggestive of ambient gas illuminated by a bi-conical distribution of ionizing radiation. Such images reveal an extended ∼13″ (∼4.1 kpc) emission-line region elongated along PA = 110°-130° (Haniff et al. 1988, 1991; Tsvetanov & Walsh 1992) with arc-like structures (Pogge & De Robertis 1995; Capetti et al. 1996; Falcke et al. 1998) contained within two wedge-shaped regions, apparently the projection of a bi-cone (Haniff et al. 1991; Pogge & De Robertis 1995; Falcke et al. 1998). Evidence for scattered nuclear continuum light is also found on both sides of the nucleus, within this bi-conical structure (Pogge & De Robertis 1993; Kotilainen & Ward 1997).

However, the gaseous kinematics reveal clear departures from this simple scenario. Long-slit spectroscopy of the emission-line region (Unger et al. 1987; Whittle et al. 1988; Durret & Warin 1990; Tsvetanov & Walsh 1992) shows that, while the ENLR gas (> 4″ [1.3 kpc] from the nucleus) follows a smooth velocity field and displays very narrow emission-lines (< 45 km s$^{-1}$, Unger et al. 1987), the NLR gas (< 4″ [1.3 kpc] from the nucleus) displays very disturbed kinematics, including much broader line profiles (100–350 km s$^{-1}$, Whittle et al. 1988). Comparison with radio continuum maps (Ulvestad & Wilson 1984; Falcke et al. 1998) shows that these disturbed areas are located in the vicinity of the northwest and southeast radio lobes (Whittle et al. 1988; Tsvetanov & Walsh 1992), suggesting that in Mrk 573, the nuclear radio ejecta perturb the gaseous kinematics of the NLR. Further evidence for an interaction between the radio ejecta and the ionized gas comes from a comparison between the highest spatial resolution emission-line images (Pogge & De Robertis 1995; Schmitt & Kinney 1996; Capetti et al. 1996; Falcke et al. 1998) and the VLA radio maps, which shows emission-line structures accompanying each of the radio features, and emission-line arcs suggestive of bow shocks.

Last, the extensive spectroscopic study of Mrk 573 by Tsvetanov & Walsh (1992) shows that the ionization parameter of the gas is roughly constant within 2″ (630 pc) of the nucleus and then increases with nuclear distance further out. Tsvetanov & Walsh (1992) attributed this increase to a rapid decline of gas density with increasing distance from the nucleus. However, using emission-line ratio maps, Capetti et al. (1996) have argued that the density decrease is not fast enough and that local sources of ionizing radiation (e.g. hot shocked gas) are required to explain the variation of ionization parameter with nuclear distance. One possible explanation is that the outflow traced by the radio ejecta is sufficiently powerful to generate ionizing radiation which is comparable to or exceeds that from the nucleus (see also Bicknell et al. 1998).

The optical studies of Mrk 573 to date have thus involved imaging at the resolutions achieved by ground-based telescopes and HST, and spectroscopy at ground-based resolutions. However, given the compact nature of the nebulosity, a detailed understanding of the physical processes associated with the interaction between radio ejecta and ionized gas requires the diagnostic power of emission-line spectroscopy combined with HST-like spatial resolution. In the present paper, we report such a study. Our observations comprise HST/WFPC2 imaging of the ionized gas in Mrk 573 in [O III]λ5007 and Hα+[N II] (some of these observations were briefly described in Falcke et al. 1998), and high-spatial resolution 3D(x,y,λ) TIGER spectroscopy of Mrk 573 in the Hβ + [O III] and Hα + [N II] + [S II] wavelength domains. We discuss the morphological, kinematical and spectral properties of the various components of the emission-line region and their relationship with the radio ejecta.

Throughout this paper, we will use a heliocentric systemic velocity of 5150 ± 11 km s$^{-1}$ (stellar Ca II triplet, Nelson & Whittle 1995) for Mrk 573. This gives a velocity relative to the cosmic microwave background of 4858 km s$^{-1}$ (–292 km s$^{-1}$ correction, NED[4] on-line velocity calculator), yielding a distance

[4]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of

and a linear scale of 65 Mpc and 315 pc per arcsec, respectively ($H_o$ = 75 km $s^{-1}$ $Mpc^{-1}$; $q_o$ = 0).

## 2. Observations and Data Reduction

### 2.1. HST imaging

#### *2.1.1. Observations*

These observations of the emission-line region of Mrk 573 have been acquired with the Wide Field and Planetary Camera 2 (WFPC2) on board HST, using the linear-ramp filters (LRF) and the Wide Field chips ($0\overset{''}{.}0996$ pixel$^{-1}$). Details of the observations can be found in Falcke et al. (1998). The central wavelengths (and FWHM bandpasses) of the LRF were 6679 Å (86 Å) and 5092 Å (66 Å) for the H$\alpha$+[N II]$\lambda$6583 and [O III] on-band images, respectively.

Using the efficiency curve of the LRF configuration, and assuming a typical [N II]$\lambda$6583/H$\alpha$ ratio of 0.8 for Mrk 573 (Tsvetanov & Walsh 1992), the [N II]$\lambda$6583 line contributes $\sim$40 % of the flux in the H$\alpha$+[N II]$\lambda$6583 image. However, as the central wavelength of the observations varies by as much as 24 Å along the major axis of the emission-line region (due to the position-dependent transmission of the LRF), the relative contributions of the H$\alpha$ and [N II]$\lambda$6583 lines to the flux in the image will change with position. The emission-line image is modified by this instrumental effect, as well as by changes in the intrinsic [N II]$\lambda$6583/H$\alpha$ ratio over the emission-line region (Tsvetanov & Walsh 1992), and wavelength shifts of the lines due to velocity gradients (e.g. Whittle et al. 1988).

In addition to the LRF images, we also used archived broad-band images (F569W, F675W, F814W, and F606W), taken on the Planetary Camera (PC) at $0\overset{''}{.}0455$ pixel$^{-1}$. Observational details for the datasets from the first three filters are given in Capetti et al. (1996), and for the last one in Malkan, Gorjian, & Tam (1998).

#### *2.1.2. Data-reduction*

Details of the data-reduction of the LRF images can be found in Falcke et al. (1998). The broad-band filter images were processed and flat-fielded with the STScI pipeline and the flux calibration was done using the header information provided. Only the F569W image was split and could have cosmic-rays removed using the IRAF/STSDAS task CRREJ. Hence, cosmic-rays rejection for the other images was done – less effectively – using the IRAF task COSMICRAYS. Alignment of the F569W, F675W and F814W images was not necessary since they were all taken at the same position on the PC.

The F569W and F675W filters contain a number of emission-lines, such as H$\beta$+[O III] and [O I]+H$\alpha$+[N II]+[S II], respectively. Because of the large equivalent width of these lines, the emission-line structure of Mrk 573 can be readily seen in the broad-band images. The F814W image was used to subtract the continuum from these images. However, since the filters are so broad and the spectral shape of the continuum changes over the image, a satisfactory continuum subtraction cannot be achieved at all points, resulting in negative fluxes in some areas. To avoid this, we scaled down the F814W image by 30% until

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Technology, under contract with the National Aeronautics and Space Administration.

the negative fluxes were removed. Unfortunately, this means that in other areas we will not have subtracted enough of the continuum. Therefore, these images which are better sampled than the LRF images because they were taken on the PC, will only be used to obtain qualitative, rather than quantitative, structural information.

#### *2.1.3. Alignment of the LRF [O III] and H$\alpha$+[N II]$\lambda$6583 images*

Since the point-spread function (PSF) is undersampled by the WFC, sub-pixel accuracy in the alignment between two LRF emission-line images is necessary for the construction of an excitation map, especially if those images contain sharp, unresolved features as seen in Mrk 573. Using the relative astrometry provided in the image headers to align the [O III] and H$\alpha$+[N II] images, we find that the central emission-line peak in the [O III] image of Mrk 573 is offset by roughly half a pixel from the H$\alpha$+[N II] peak. A similar offset is found for two off-nuclear isolated blobs. For this alignment, the excitation map, obtained by clipping both the [O III] and H$\alpha$+[N II] images at 3 times the r.m.s. noise and dividing the former by the latter, displays unusually high [O III]-to-(H$\alpha$+[N II]$\lambda$6583) ratios in extremely narrow structures, which are almost certainly artefacts resulting from image misalignment. This strongly suggests that the apparent offset between the [O III] and H$\alpha$+[N II] peaks is not real (in particular, it is not due to reddening) and should be corrected.

To check that the shift-vector derived from a comparison of the positions of individual features in the [O III] and H$\alpha$+[N II] images was correct, we have used the following procedure which provided us with a second estimate of the shift-vector. We first calculated an array of excitation maps in which the H$\alpha$+[N II] image was shifted by various fractions of a pixel with respect to the position derived from the relative HST astrometry. For each of these excitation maps, we then calculated the sum, $\Sigma$, of all the ratios [O III]/(H$\alpha$+[N II]) which are greater than 2. For sharp structures in the image, even a slight error in the alignment between [O III] and H$\alpha$+[N II] maps increases $\Sigma$ by artificially creating areas of apparent high excitation. Hence, we selected the shift-vector for which $\Sigma$ had a minimum value. This method yielded essentially the same shift as determined from comparing the positions of individual features. It is noteable that, because the emission-line structure of Mrk 573 is dominated by thin arcs, most of which are elongated roughly north-south, the shift-vector was much better determined in the east-west direction ($\pm$0.15 pixel) than in the north-south direction ($\pm$0.3 pixel). The fact that these two different methods yield the same shift-vector gives us confidence that the offset was indeed a consequence of uncertainties in the internal astrometry of HST, resulting from the telescope moves between the different LRF exposures.

### 2.2. TIGER 3D spectroscopy

#### *2.2.1. Observations and data-reduction*

These 3D (x,y,$\lambda$) observations of Mrk 573 have been obtained at the Canada France Hawaii Telescope on 1993 November 19 and 20, using the TIGER integral field spectrograph. A detailed description of the instrument, which uses a compact array of more than 300 circular micro-lenses, can be found in Bacon et al. (1995). Two overlapping fields, one centered east and the other west of the nucleus, have each been observed in two different spectral configurations (Table 1), one centered at 5000 Å (B configuration) and the other at 6750 Å (R configuration). With a total field of view of $11'' \times 6''$ centered on the nucleus, we cover the whole radio structure (Ulvestad & Wilson 1984; Falcke et al. 1998) and the inner bright structures of the emission-line region (Pogge & De Robertis 1995; Capetti et al. 1996). The spatial sampling was $0\farcs39$ per lens, with a seeing limited resolution of $\sim 0\farcs9$-$1\farcs0$.

The data-reduction has been performed using the TIGER software (Rousset 1992) under the ESO-MIDAS environment. Residuals from the wavelength calibration relation were smaller than 0.1 Å in both spectral configurations, much smaller than the 1.8 Å size of the spectral pixel. The absolute wavelength calibration of the R configuration has been checked using sky lines and found to be accurate to within 10-20 km s$^{-1}$. Comparison of the H$\alpha$ (R configuration) and H$\beta$ (B configuration) centroid velocities at various locations in our field of view has shown a $-50$ km s$^{-1}$ systematic shift of the B configuration relative to the R configuration. In view of the accuracy of the R configuration wavelengths noted above, we have assumed this shift is an instrumental effect in the B configuration data and have corrected for it, by adding 50 km s$^{-1}$ to the H$\beta$ and [O III] velocities. In the following, all the cited velocities are heliocentric (a correction of $-17$ km s$^{-1}$ having been applied for the motion of the earth).

The spectra were flux calibrated by means of observations of the standard stars HD 19445 and Hiltner 600. Comparison of their spectra shows that differences in the flux calibration are $< 6$ %. Integrating our data over a $2\farcs7 \times 4\farcs0$ aperture centered on the nucleus, we derive $F_{H\beta} = 5.9 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ and $F_{H\alpha+[NII]\,\lambda\lambda\,6548,6583} = 5.2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, which are 14% and 10% higher than the fluxes from Koski (1978), respectively. This is consistent with the differences of up to 20% reported by Capetti et al. (1996) and Pogge & De Robertis (1995) when comparing their observations with Koski's fluxes. Comparison of the TIGER data with our set of HST emission-line images (see Sect. 2.1) shows differences in flux of 15 % ([O III]) and 11 % (H$\alpha$+[N II]).

As Mrk 573 filled our field of view, preventing us from deriving a sky spectrum free of contamination by the galaxy, sky subtraction of the R configuration spectra has been performed using the following procedure. We first constructed a spatially averaged spectrum which minimizes the contribution of the galaxy by summing together spectra in regions where the galaxy is faint. A Gaussian fit to the sky and galaxy lines present in this high signal to noise ratio spectrum was then performed (the wavelengths of the sky emission-lines were taken from Osterbrock et al. 1996). Last, the resulting synthetic sky spectra (one for each data cube of the R configuration) derived from the fit have been subtracted from each spectrum of the R1 and R2 data cubes. Figure 1 shows one of the two synthetic sky spectra and outlines the weakness of sky lines compared to the noise in our data.

The two overlapping fields in each spectral configuration have been combined using the continuum peak of the galaxy as a reference. The isophotes in the region of overlap were carefully examined to check the alignment. The final data cubes consist of 570 (B configuration) and 540 (R configuration) flux calibrated spectra.

#### *2.2.2. Analysis of the spectral data*

The continuum in both the R and B configuration spectra was fitted with a straight line across line-free wavelength segments and removed. Contamination by stellar absorption is a potential problem for only the H$\beta$ emission-line, which has equivalent widths (EW) ranging from 15 to 50 Å in the regions of interest, whereas the H$\beta$ absorption line has a typical EW of 4.5-6.5 Å, as estimated from the E7 and E8 stellar templates of Bica et al. (in Leitherer et al. 1996), which provide a correct match (especially the template E7) to the shape of the continuum in the 3000–7000 Å nuclear spectrum of Mrk 573 obtained by Storchi-Bergmann et al. (1996, see their Fig. 3, upper panel). For H$\alpha$, the typical EW of the absorption-line estimated in the same way is 2-2.5 Å, while the EW of the emission line ranges between 30 and 230 Å over the emission-line region.

The basic spectral parameters of the emission-lines (intensity, centroid velocity and FWHM) were derived from single component Gaussian fitting of the lines using the FIT/SPEC software (Rousset 1992). Lines from doublets ([O III]$\lambda\lambda$4959,5007, [N II]$\lambda\lambda$6548,6583 and [S II]$\lambda\lambda$6717,6731) were forced to have the same width and velocity, as well as fixed or bounded ratios when relevant ([O III]$\lambda$5007/[O III]$\lambda$4959 = 2.88; [N II]$\lambda$6583/[N II]$\lambda$6548 = 2.94; 0.35 < [S II]$\lambda$6717/[S II]$\lambda$6731 < 1.5). In the following, all the FWHM given in Å are 'as measured', i.e. without any correction for instrumental resolution, while the FWHM given in km s$^{-1}$ have been corrected for instrumental resolution by subtraction of 3.6 Å in quadrature.

### *2.2.3. Deconvolution of the TIGER data cubes*

The PSF of our TIGER observations, modelled as the sum of two co-aligned Gaussian functions of different widths and intensities, has been estimated using the HST emission-line images. In this computation, we have used a non-linear least-square algorithm, comparing the emission-line image derived from the TIGER data cube integrated over the HST filter bandpass with the HST emission-line image convolved by various estimates of the PSF. Note that this process also provided and allowed correction of any shift and/or rotation of the TIGER data cube relative to the HST image. The PSF parameters (FWHM core/FWHM halo/ratio of halo to core intensity peaks) are found to be $0\farcs95/1\farcs9/0.22$ and $1\farcs05/2\farcs3/0.07$ for the R and B configurations, respectively.

To improve the spatial resolution of the ground-based 3D data cubes, we have deconvolved our continuum subtracted TIGER data cubes, resampled onto square pixels, using a new method developed in a collaboration between the University of Maryland, the CRAL - Observatoire de Lyon and L.B. Lucy (Ferruit et al. 1999, in preparation). This method is based on a Richardson-Lucy algorithm (Richardson 1972; Lucy 1974) modified to use the high angular resolution HST emission-line images as a guide for the deconvolution process, following suggestions by Lucy (1997, private communication). Basically, this modified Richardson-Lucy algorithm will favor solutions in which the HST emission-line image is recovered when the deconvolved ground-based data are integrated over the range of wavelength included in the HST image (the integration being weighted by the throughput of the HST/LRF at each wavelength).

This 'guided deconvolution' method has been tested on only a few astrophysical examples and not yet through extensive application to artificial data cubes. Such a complete study of the method will be published in a forthcoming paper (Ferruit et al. 1999, in preparation). We have therefore performed a deconvolution of each of the [O III]$\lambda$5007 and H$\alpha$+[N II] data cubes of Mrk 573 in three different ways. The first method was a pure Richardson-Lucy deconvolution, each velocity slice of the data cube being deconvolved independently using the known PSF and a classical Richardson-Lucy algorithm. The second and third methods were a 'weakly guided' deconvolution in which the guiding term (which forces the deconvolved TIGER image to correspond to the HST image) is weighted by a coefficient $\alpha = 0.1$, strongly reducing its impact on the deconvolution process, and a 'strongly guided' deconvolution with full implementation of the guiding term ($\alpha = 1$).

Figure 2 shows the original data and the results of these three deconvolutions for the [O III]$\lambda$5007 line of Mrk 573. We display the [O III] line intensity, centroid velocity and FWHM maps derived from single Gaussian fitting of the [O III]$\lambda$5007 line in each spectrum of the original TIGER data (top row), as well as of each spectrum of the three deconvolved data cubes (second, third and fourth rows). As expected, an excellent match to the [O III] HST image (see Fig. 3) is obtained using the 'strongly guided' method (Fig. 2, bottom row), which also seems to achieve the best spatial resolution in the velocity and FWHM maps (e.g. the strongly blueshifted feature $\simeq 1\farcs2$ northwest of the nucleus is split into two knots). The two other methods (pure Richardson-Lucy, second row, and 'weakly guided', third row) give results similar to those of the 'strongly guided' method, but with lower spatial resolution. We emphasize that all the features discussed in this paper are present in all three deconvolved data cubes. Some features, like the blueshifted gas $\simeq 1\farcs2$ northwest of the nucleus are apparent in the original TIGER data cube before deconvolution (Fig. 2, top row), as well as in lower spatial resolution spectrographic data from the literature (Whittle et al. 1988; Tsvetanov & Walsh 1992).

To avoid the possibility of introducing spurious features due to possible ambiguities in the guided method, while still taking advantage of the additional constraint provided by the HST image, we have decided to base our discussion on the results of the 'weakly guided' method, but using 300 iterations instead of the 150 used in the test. This method also has the advantage of minimizing the effects of changes in the LRF bandpass with position on the WFC, which may lead to unreliable results in the guided images. Therefore, in the following, the [O III], [N II] or H$\alpha$ deconvolved data will refer to the data cubes obtained with 300 iterations using the 'weakly guided' method. Applying to the deconvolved [O III] data cube the same method than used for the original (not deconvolved) data cubes (see above), we find that, for this cube, the spatial PSF after deconvolution has a Gaussian profile, with a FWHM of $\sim 0\farcs35$.

HST images are not available in the H$\beta$ and [S II]$\lambda\lambda$6717,6731 lines, so no guided deconvolution was possible and the data cubes have been deconvolved using a pure Richardson-Lucy method (150 iterations). The PSF was taken from the neighbouring [O III] (for the H$\beta$ cube) and H$\alpha$+[N II] (for the [S II] cube) data cubes.

## 3. Results

### 3.1. HST imaging

Figures 3 (top panels) and 4 show the HST emission-line images. The emission-line region of Mrk 573 is seen to consist of a bright, elongated central peak and two pairs of arcs which are connected by knotty features. In the following, we will label the arcs as SE2-arc, SE1-arc, NW1-arc, and NW2-arc, from the southeast end to the northwest end of the emission-line region (see Fig. 5). The strings of knots will be labelled similarly, as SE2-knots, SE1-knots, and NW1-knots (Fig. 5). Overall, the same structures were seen in the Faint Object Camera images of Capetti et al. (1996). Note that, however, in the higher spatial resolution [O III] images of Capetti et al. (1996, Fig. 1a), the elongation to the southeast of the central peak is spatially resolved into a distinct, off-nuclear component which we will consider hereafter as part of SE1-knots.

In the PC emission-line images (Fig. 4), two narrow absorption features are present immediately north and northwest of the nucleus, running roughly perpendicular to the major axis of the emission-line region. The inner two arcs (SE1-arc & NW1-arc) are very narrow and apparently are not resolved transversely. A third pair of arcs (labelled SE3-arc and NW3-arc) is present $9\farcs4$ from the nucleus (Durret & Warin 1990; Pogge & De Robertis 1995), but are outside our field of view. Note that SE3-arc and NW3-arc coincide with the beginning of small H$\alpha$ spiral arms (Pogge & De Robertis 1995).

Figure 3 (bottom left panel) shows an excitation map in which dark areas correspond to high

[O III]-to-(H$\alpha$+[N II]$\lambda$6583) ratios as derived from the LRF images. This map (see also Fig. 11 in Falcke et al. 1998) shows very clearly the double wedge form expected if the gas is photoionized by a beamed nuclear ionizing continuum. As one can see from Table 2 and Fig. 3, the various emission-line features display quite different excitation levels. While the [O III]-to-(H$\alpha$+[N II]) ratio is relatively low in the innermost two arcs (SE1-arc and NW1-arc), it is higher in the next two arcs (SE2-arc and NW2-arc). The strings of knots display [O III]-to-(H$\alpha$+[N II]) ratios inbetween those of the inner and outer arcs. There is a strong north-south gradient in the [O III]-to-(H$\alpha$+[N II]) ratio along NW2-arc.

In Table 2, we have listed the main components visible in the emission-line images and their properties. We outlined each feature manually and determined the radial offsets of their midpoints from the continuum peaks (assumed to coincide), their [O III] fluxes, their relative contribution to the total [O III] flux, and the range of [O III]-to-(H$\alpha$+[N II]) ratios. For most features the encircled area given in Table 2 is best treated as an upper limit, as the areas are sensitive to the WF camera resolution.

Figure 6 (top left panel) shows the 2 cm radio continuum isophotes (Falcke et al. 1998) overlaid on the [O III] image. The peak of the central flat-spectrum radio-blob (Falcke et al. 1998) has been aligned with the optical continuum peaks of our images. It is noteable that the optical continuum peak need not be the true nucleus of the galaxy due to the dust lane close to it (Fig. 4; see also Capetti et al. 1996). A point-like nuclear source is detected in the mid-infrared L$'$ band by Alonso-Herrero et al. (1998), and probably coincides with the nucleus, but no accurate position is available. With our adopted registration, the northwest radio component is almost coincident with the NW1-knots, while the southeast radio component coincides with the SE1-arc, close to the beginning of the SE2-knots. The curvature of the SE1-knots is very similar to the curvature of the elongation to the southeast of the nuclear radio component seen in both the 2 cm and 3.5 cm radio maps (Falcke et al. 1998). The SE1-knots also point toward the southeast radio component. This strongly suggests that the inner arcs and knots are directly related to the radio material.

Finally, we want to remark that despite the very elongated structure of the emission-line region and the presence of a wedge-shaped ionization structure, there are several axes in the images. The two inner strings of knots (SE1-knots and NW1-knots), for example, define directions that seem to be inclined with respect to the central axis of the wedge and point rather towards the northern tip of the north-west wedge, and the southern end of the south-east wedge. There is also a faint spur of [O III] emission extending over $2''$ from the eastern edge of SE2-arc to the edge of our field of view (Fig. 3). This feature is present in the ground-based [O III] images of Pogge & De Robertis (1995, their Fig. 4) and links SE2-arc to SE3-arc. The fact that it does not appear in our H$\alpha$+[N II] image (Fig. 3) suggests that it is a region of high [O III]/(H$\alpha$+[N II]) ratio. A counterpart to this spur, to faint to be detected in the HST images, is seen exactly opposite to it (Pogge & De Robertis 1995, their Fig. 4), extending from the western edge of NW2-arc, where one sees higher [O III]/(H$\alpha$+[N II]) ratios in our excitation map (see Fig. 3), to the beginning of NW3-arc. These inner knots and outer spurs define an X-shape centered approximately on the nucleus.

### 3.2. Spectroscopy

#### *3.2.1. [O III]$\lambda$5007 line and gaseous kinematics*

Of the spectral lines available in our TIGER observations of Mrk 573, [O III]$\lambda$5007 combines the advantages of being strong (i.e. having a good signal to noise even in the deconvolved data cube) and isolated (i.e. yielding less ambiguity for the final data cube[5]). Therefore, the [O III] deconvolved data cube will be our primary source of information on the gaseous kinematics.

The results of single component Gaussian fitting of the deconvolved [O III] data cube ('weakly guided' method, 300 iterations) are shown in Fig. 6. Most of the features present in the HST [O III] images (top left) can be found in the [O III] map reconstructed from the deconvolved data cube (top right), despite the worse spatial resolution of the latter. The middle right and bottom right panels of Fig. 6 display the [O III] velocity field and FWHM map, respectively, as derived from the same single component Gaussian fitting of the deconvolved [O III] data cube. To show the relative locations of features seen in these maps, their contours are shown superimposed on the [O III] intensity image in the middle left and bottom left panels.

The second pair of arcs (SE2-arc and NW2-arc) displays a smooth velocity pattern consistent with the ENLR velocity field previously observed between $4''$ and $6''$ (Unger et al. 1987; Whittle et al. 1988; Durret & Warin 1990; Tsvetanov & Walsh 1992). If this smooth velocity pattern traces rotational motion of the ENLR gas, as suggested by previous authors (Durret & Warin 1990; Tsvetanov & Walsh 1992), the kinematical major axis PA of the ENLR gas is $\sim$60°-90°, which is different from the PA of $\sim$30°-40° inferred by Tsvetanov & Walsh (1992).

Within a radius of $2''$ from the nucleus, three regions of strong deviation from the smooth velocity pattern are seen along the emission-line region major axis. The two perturbations southeast of the nucleus are redshifted with respect to the systemic velocity, in an area where blueshifted gas is expected from the extrapolation of the ENLR velocity field into the nuclear regions. These regions will be labelled SE2-red (a weak velocity deviation at $\sim2\farcs1$ [660 pc] projected radius, see Fig. 7) and SE1-red (a strong velocity deviation at $<0\farcs8$ [250 pc] projected radius, see Fig. 7). Northwest of the nucleus, at $\sim1\farcs1$ [360 pc] projected radius, the [O III] gas displays the strongest blueshifts observed in our entire field of view, peaking at $-320$ km s$^{-1}$ relative to the systemic velocity. This region will be labelled NW1-blue (see Fig. 7). While the highly blueshifted gas at NW1-blue has been detected in previous lower spatial resolution obervations (Whittle et al. 1988; Tsvetanov & Walsh 1992), this is the first time that the weaker deviations SE1-red and SE2-red have been clearly detected. The existence of SE1-red was only suggested by the extended red wings observed in the [O III] line south of the nucleus by Whittle et al. (1988).

Figure 6 (middle left) shows that SE1-red and NW1-blue are located within the two inner arcs (SE1-arc and NW1-arc), while SE2-red is located on the outer-edge of SE1-arc and is possibly associated with SE2-knots. It is noteable that these three velocity perturbations are not coincident with any high [O III] surface brightness features. Comparison with the 3.6 cm radio continuum map of Falcke et al. (1998) shows, however, that each of the three velocity features is located close to one of the three strong radio components (Fig. 6, middle right).

The FWHM map (Fig. 6, bottom right) shows that the outer arcs (SE2-arc and NW2-arc) have narrow line widths, as expected if they are ambient, photoionized gas. Surprisingly, the FWHM map does not peak at the nucleus, but the regions of highest FWHM form a ring around the nucleus of Mrk 573, inside the two inner arcs (SE1-arc and NW1-arc), at radii similar to that of the north-west radio lobe. These locations of increased FWHM correspond to the locations of the SE1-red and NW1-blue velocity deviations. Last, a small increase in FWHM is also associated with SE2-red.

To compare the kinematical and spectral properties of the various components present in these

[5]The flux in the HST narrow-band [O III]$\lambda$5007 image used to guide the deconvolution is distributed over a single line instead of the three lines in the H$\alpha$+[N II] configuration.

maps, we have selected a set of eight representative locations (four arcs, the nucleus, and three velocity perturbations), the positions of which are listed in Table 3. Spectra averaged over $0\farcs2$ diameter apertures centered on these locations have been extracted from the deconvolved data cube and used to derive the kinematical and spectral characteristics of each of these components. Figure 7 shows the [O III]$\lambda$5007 velocity profile for each component as well as their location on the [O III] intensity and velocity maps. A strong red (blue) wing, extending up to 700 km s$^{-1}$(–800 km s$^{-1}$), is seen in the spectrum of SE1-red (NW1-blue), consistent with the extended wings observed by Whittle et al. (1988) in their high spectral resolution [O III] profiles. Results of single component Gaussian fitting of these spectra are displayed in Fig. 8 and listed in Table 3.

The [O III] velocity at the nucleus is 5140 km s$^{-1}$, which is indistinguishable of the stellar systemic velocity of 5150 km s$^{-1}$(Nelson & Whittle 1995). Comparison of the continuum and [O III] maps reconstructed from our original (not deconvolved) B configuration observation, shows a $0\farcs2$ shift (along PA $\sim 160°$) of the [O III] peak relative to the continuum peak. Such a shift was reported in Whittle et al. (1988) and results from the bright inner [O III] knots to the southeast of the nucleus (SE1-knots, see Fig. 5).

As SE2-red, SE1-red and NW1-blue lie nearly along PA = 125°, we can use the velocity gradient of 16 km s$^{-1}$ arcsec$^{-1}$ derived by Durret & Warin (1990) along this PA as a reference to estimate the deviations of the velocities of these three features from the ambient velocity field. Using the locations and centroid velocities listed in Table 3, we find deviations of the velocity centroids of +60 km s$^{-1}$ (SE2-red), +140 km s$^{-1}$ (SE1-red) and –460 km s$^{-1}$ (NW1-blue). Application of the same procedure to SE2-arc, which is likely part of the ENLR and should therefore show little deviation from the ambient velocity field, yields a deviation of -80 km s$^{-1}$. This might indicate that the velocity gradient derived from Durret & Warin's (1990) data is too low because of their relatively low spatial resolution.

### *3.2.2. Hβ emission-line*

Figure 9 shows the results of single component Gaussian fitting to the original (not deconvolved) TIGER H$\beta$ data cube. Due to the lower signal to noise of this weaker line (compare the H$\beta$ intensity map of Fig. 9 with the corresponding [O III] map displayed in Fig. 2, top left panel), we have not been able to derive a reliable high spatial resolution map from the deconvolved data cube. Nevertheless, the gross features of the H$\beta$ intensity, velocity and FWHM distributions (Fig. 9) agree well with the corresponding distributions for [O III] (Fig. 6). H$\beta$ spectra and single component Gaussian fits of the eight regions defined in Fig. 7 are displayed in Fig. 10, but the low signal to noise ratio of these spectra extracted from the deconvolved H$\beta$ data cube makes most of the fitting results listed in Table 3 uncertain.

### *3.2.3. Hα and [N II]λλ6548,6583 emission-lines*

Figure 11 displays the reconstructed maps of the intensity (left), velocity (middle) and FWHM (right) of H$\alpha$ (top panels) and [N II]$\lambda$6583 (bottom panels) as derived from single component Gaussian fitting of the deconvolved H$\alpha$+[N II] data cube ('weakly guided' method, 300 iterations). Although somewhat noisier than their [O III] equivalents, these maps contain all the features seen in the [O III] maps, except the weak SE2-red component. The H$\alpha$+[N II] spectra at the eight selected locations and their single component Gaussian fits are shown in Fig. 12, while numerical values (centroid velocities, FWHMs and [N II]$\lambda$6583/H$\alpha$ ratios) are listed in Table 3.

The derived H$\alpha$ and [N II] velocities are in good agreement with the [O III] velocities for the arcs and the nucleus, but the velocity deviations from the ambient rotation curve at SE2-red, SE1-red and NW1-blue seem smaller for these two lower excitation lines than for [O III]. In both the H$\alpha$ and [N II] lines, the NW1-blue region is less extended than in [O III] and is shifted by a few tenths of an arcsecond to the north compared to its location in [O III]. Unfortunately, one has to be cautious when comparing the results of two different deconvolved data cubes, as it is difficult to disentangle real differences from differences in spatial resolution.

As for the [O III] line, the second pair of arcs (SE2-arc and NW2-arc) is part of a smooth velocity field and exhibits relatively narrow line widths (see Table 3), suggesting that they mark the beginning of the kinematically less disturbed ENLR. They also differ from the regions closer to the nucleus (i.e. the NLR) in having lower [N II]$\lambda$6583/H$\alpha$ ratios (0.4-0.5 instead of 0.7-1.0 for the inner regions, see Table 3). This is consistent with the results of Tsvetanov & Walsh (1992), who found a decrease of the [N II]/H$\alpha$ ratio with projected radial distance from the nucleus. The [N II] and H$\alpha$ lines are narrower than the [O III] lines in the NW1-arc (corrected FWHM of 160, 140 and 230 km s$^{-1}$ for [N II], H$\alpha$ and [O III], respectively).

### *3.2.4. [S II]$\lambda\lambda$6717,6731 emission-lines*

The last lines available in our data set are those of the [S II]$\lambda\lambda$6717,6731 doublet, the ratio of which is a density indicator. As for H$\beta$, the weakness of these lines has prevented us from obtaining accurate high spatial resolution maps using the deconvolved [S II] data cube. Therefore, Fig. 13 shows the results of single component Gaussian fitting to the lines in the original (not deconvolved) [S II] data cube.

The top panels of Fig. 13 show the intensity maps in the individual [S II]$\lambda$6717 (left) and [S II]$\lambda$6731 (right) lines. As for the [O I]$\lambda$6300 emission-line images of Pogge & De Robertis (1995), the two inner arcs (SE1-arc and NW1-arc) are more prominent in these [S II] images than in the [O III] or H$\alpha$ images, witnessing the peak in [S II]$\lambda\lambda$6717,6731/H$\alpha$ ratio detected at these locations (Tsvetanov & Walsh 1992). The signature of the ambient velocity field is clearly seen in the outer regions of this $0\farcs9$-$1\farcs0$ resolution velocity map (Fig. 13, middle left). As for [O III], and assuming that this velocity field traces rotational motions, the inferred kinematical major axis PA is between 60° and 90°, which is different from the PA of 30°-40° measured by Tsvetanov & Walsh (1992) at larger distances from the nucleus. Although diluted by the lower spatial resolution, the SE1-red and NW1-blue velocity components are also present, but no trace of SE2-red.

The FWHM map (Fig. 13, middle right) shows the contrast between the narrow lines of the second pair of arcs (SE2-arc and NW2-arc) and the broader lines of the inner regions. Even at this spatial resolution, the nucleus is not associated with the regions of maximum FWHM, which in fact straddle it. There is a 'finger' of increased FWHM extending southeast from SE1-arc into SE2-arc, which may be related to the SE2-red component.

The bottom panels of Fig. 13 show the [S II]$\lambda$6717/[S II]$\lambda$6731 ([S II] ratio hereafter) map, overlaid with isophotes of [S II]$\lambda$6717 intensity (left) and [S II] isovelocity contours (right). Lower values of the [S II] ratio (i.e. darker regions in the figures) correspond to higher gas densities, with high and low density limit ratios of $\sim$0.4-0.5 and $\sim$1.4-1.5, respectively. The SE1-arc and NW1-arc form the boundaries of a region of higher density gas, while the SE2-arc and NW2-arc exhibit [S II] ratios close to the low density limit.

Figure 14 displays the [S II]$\lambda\lambda$6717,6731 spectra extracted from the [S II] deconvolved data cube

(Richardson-Lucy method, 150 iterations), overlaid with their single component Gaussian fits. The derived centroid velocities, FWHM and [S II] ratios are listed in Table 3. The nuclear spectrum indicates a velocity close to systemic, consistent with the results inferred from the other lines, and a high density of 3600 $cm^{-3}$. The two inner arcs display intermediate densities – 850 $cm^{-3}$ (SE1-arc) and 580 $cm^{-3}$ (NW1-arc). Note that, as for the H$\alpha$ and [N II] lines, NW1-arc exhibits a small width of $\sim$ 140 km $s^{-1}$ in the [S II] lines.

The signal to noise achieved in the SE2-red, SE1-red and NW1-blue velocity components is poor (see Fig. 14), preventing us from deriving an accurate estimate of the density in these regions. We can only say that these regions seem to display broader lines than the others, a result in good agreement with what we see for the other lines. Last, the [S II] spectra of SE2-arc and NW2-arc indicate low densities and narrow line widths (see Table 3), our results being once more limited by the low signal to noise of these spectra.

#### *3.2.5. Line ratios and gas density*

Taking advantage of the good spatial resolution and coverage achieved in our TIGER observations even without deconvolution, we have built diagrams similar to those presented by Tsvetanov & Walsh (1992), tracing the evolution of various line ratios as a function of the projected radial distance from the nucleus. We have used the minor axis of the emission-line region in PA = 35° as a separator, defining a southeast side (negative radii) and a northwest side (positive radii). Figure 15 (top left panel) displays the distribution of [O III]$\lambda$5007 intensity as a function of the projected radial distance from the nucleus. In addition to the central peak at the nucleus, four secondary peaks are seen at radii roughly corresponding to those of the emission-line arcs and are labelled accordingly.

As mentioned in Sect. 2.2.2, contamination of the H$\beta$ emission-line by stellar absorption is a concern. We have therefore corrected the H$\beta$ emission-line fluxes for this absorption by assuming a constant equivalent width of 5.5 Å (an average of the 4.5 and 6.5 Å values estimated in Sect. 2.2.2) for the stellar H$\beta$ absorption line . The [O III]/H$\beta$ ratios before (black crosses) and after (blue and red symbols) correction are displayed in Fig. 15 (middle left panel). Low signal to noise ratios have been rejected by clipping the H$\beta$ and [O III]$\lambda$5007 peak fluxes (as derived from the single component Gaussian fitting) at $0.4 \times 10^{-15}$ erg $s^{-1}$ $cm^{-2}$ $Å^{-1}$ $arcsec^{-2}$ (i.e. $\sim$13 $\sigma$) before division.

Before correction, the [O III]$\lambda$5007/H$\beta$ ratio peaked at the nucleus and decreased steadily with projected radius, with ratios in the 10 to 15 range. After correction, the [O III]/H$\beta$ ratio is roughly constant ($\sim$10) within 2″ of the nucleus, with a slight increase at the location of the nucleus, where it reaches values of $\sim$10–12. Note the relatively large scatter of the points, even close to the nucleus, which is at least partly due to the combination of the poor signal to noise ratio in H$\beta$ and the uncertain correction for contamination by the H$\beta$ stellar absorption line.

The [N II]$\lambda$6583/H$\alpha$ (middle right panel) and [S II]$\lambda\lambda$6717,6731/H$\alpha$ (bottom left panel) line ratios display very similar behaviors, with a minimum at the location of the nucleus, and maxima close to the inner arcs. The gas density (bottom right panel), as derived from the [S II] ratio, decreases with increasing radial distance from the nucleus. This largely confirms the results of Tsvetanov & Walsh (1992), but with improved spatial resolution and more extensive spatial coverage. The decrease of the gas density with increasing nuclear distance is steeper to the southeast of the nucleus than to the northwest.

## 4. Discussion

### 4.1. The nucleus

The nucleus (see Fig. 5) exhibits a centroid velocity close to systemic and the line profiles from all four sets of ionic species, although broad (330-440 km s$^{-1}$, Table 3), are narrower than at SE1-red and NW1-blue (see Fig. 6). The nuclear lines also do not display the broad wings seen in these regions.

In the inner 2″-3″(630-950 pc), the line ratios built from our data cubes (see Fig. 15) indicate that, in the context of simple photoionization models, the ionization parameter of the gas increases toward the nucleus (see Sect. 4.3.2 and Fig. 17), consistent with the results of Tsvetanov & Walsh (1992). The nuclear and circumnuclear spectra of Mrk 573 (from Storchi-Bergmann et al. 1996) have also been successfully modelled with a mixture of matter-bounded and ionization-bounded (MB-IB) clouds photoionized by the nuclear radiation (Binette, Wilson, & Storchi-Bergmann 1996). These more sophisticated photoionization models successfully reproduce the relatively high [O III] temperature observed in both the nuclear and circumnuclear regions of Mrk 573 (13000-17000 K, Tsvetanov & Walsh 1992; 12000-13000 K, Wilson, Binette, & Storchi-Bergmann 1997), as well as its difference from the [N II] temperature (∼9000 K, Wilson et al. 1997). We should, however, bear in mind that the nuclear spectrum of Mrk 573 obtained by Storchi-Bergmann et al. (1996) is integrated over a 2.″8×1.″5 region with 1″ seeing, and hence includes the inner knots and arcs (see relative fluxes of the components in Table 2). The unresolved nucleus (see Fig. 5) may contain gas of sufficiently high density that the $^1D_2$ levels of $O^{+2}$ and $N^{+1}$ suffer collisional de-excitation, rendering temperature determinations assuming the gas is in the low density limit unreliable. However, this effect is unlikely to be important in the above referenced temperature determinations, because of the relatively small contribution of the unresolved nucleus to the measured line fluxes (see Table 2).

From the observed line ratios, we have no way of determining whether the photons which ionize the gas in the unresolved nucleus originate in a compact central source or in extended photoionizing shocks[6]. However, given the absence of a strong kinematical signature of the interaction between the radio ejecta and the ambient gas in the nuclear spectrum, we favor a scenario in which the energy budget of the nuclear ionized gas is dominated by photoionization by the central source.

### 4.2. The narrow line region

We will consider the narrow line region to comprise those parts of the emission-line nebulosity with [O III]λ5007 line FWHM (corrected for instrumental broadening) > 200 km s$^{-1}$. This region extends 2.″5 (790 pc) southeast and northwest of the nucleus, and includes the morphological features SE2-knots, SE1-arc, SE1-knots, NW1-knots and NW1-arc (see Fig. 5) and the spectroscopic features SE2-red, SE1-red and NW1-blue (see Fig. 7). In the following, we first discuss the nature of the strings of knots and then consider models for the arcs in which the gas is ionized either by 'external' photons (e.g. produced by the AGN), or by photons created 'in situ' by shocks in the outflow.

[6]As outlined by Allen, Dopita, & Tsvetanov (1998), the classical optical line ratios alone cannot distinguish between shock+precursor and classical photoionization models.

#### *4.2.1. The knots – signatures of jet/ambient medium interactions ?*

The small sizes of the strings of knots and the proximity to the nucleus of SE1-knots and NW1-knots, make them more difficult to study than the arcs. They comprise a distribution of bright emission-line knots, possibly linked by low luminosity filaments (Capetti et al. 1996; see also Fig. 3 and 5). One of the knots of NW1-knots is resolved into an arc-like structure in the high-spatial resolution FOC [O II] and [O III] images of Capetti et al. (1996).

As emphasized by Capetti et al. (1996), the morphology of the inner strings of knots of Mrk 573 is reminiscent of that of the inner regions of NGC 1068. The inner knots are also the locus of strong kinematical disturbances (SE1-red and NW1-blue), similar to (although weaker than) those observed in NGC 1068 (Pécontal et al. 1997; Axon et al. 1998). These kinematic disturbances have been interpreted as the result of interactions between jets and the interstellar gas (e.g. Pécontal et al. 1997; Steffen et al. 1997b; Axon et al. 1998; Bicknell et al. 1998).

One of the primary manifestations of a jet can be the presence of a hot expanding cocoon of shocked jet material, driving shocks into the ambient medium. This interaction between the cocoon and the ambient medium may produce clumps of dense gas in a shell-like structure around the cocoon (Steffen et al. 1997a). For a cylindrical cocoon, the predicted emission-line profiles are symmetric and we would have to be observing only one side of the cocoon to see the redshifts and blueshifts associated with SE1-red and NW1-blue, respectively. Such a situation can arise if the jet is propagating in a stratified medium (e.g. the expected gradient of density perpendicular to the galaxy disk), with the denser side dominating the emitted spectrum. However, in Mrk 573, the northwest side of the emission-line region is less reddened and believed to be in front of the galaxy disk (Tsvetanov & Walsh 1992; Storchi-Bergmann et al. 1996). Thus, the dense side of the northwest cocoon would be expected to be receeding, whereas the observations show that NW1-blue is blueshifted. Therefore, it seems unlikely that the inner knots reflect the expansion of a jet cocoon.

Bright optical knots and filaments (as well as radio hot spots) can also be created during the interaction of a jet with ambient gas clouds (e.g. Blandford & Königl 1979; Wilson 1982; Allen 1984). This scenario is supported by the fact that the bright emission-line knots are associated with radio hot spots, as well as with changes in the direction of the radio 'jet' (Falcke et al. 1998; see Sect. 3.1). This suggests that the knots may trace the deflection of the radio jet by individual clouds (as modelled by, e.g. Bicknell et al. 1998). An interaction between a jet and a dense might easily account for the velocity shifts seen at SE1-red and NW1-blue, with the southeast jet receding and the northwest jet coming toward us. Although the [O III]/[O II] ratio increases by more than a factor of two at the location of one of the knots of NW1-knots (Fig. 3, bottom panel, in Capetti et al. 1996), other line ratios, such as [O III]/(H$\alpha$+[N II]$\lambda$6583), are roughly constant in the central $1''$-$1''\!.5$ (Fig. 3, bottom left). Therefore, in Mrk 573, such a jet-cloud interaction is not associated with changes in the gaseous excitation as dramatic as seen in NGC 1068 (e.g. cloud G, see Fig. 3 in Pécontal et al. 1997). High spatial resolution observations of higher excitation lines would be helpful in this connection. In this scenario, the association between SE2-knots and SE2-red would trace the deflection of a weaker jet (created by an older nuclear ejection), perhaps driving a bow shock seen as SE2-arc. Last, the arc-like sub-structure in NW1-knots (see Fig. 1 in Capetti et al. 1996) is very similar to what is obtained in the numerical simulations of Steffen et al. (1996) if the head of the jet is currently impinging on a dense cloud.

### *4.2.2. Central source photoionization models for the inner arcs*

In the following, we consider models in which the gas in SE1-arc and NW1-arc is photoionized by a compact nuclear source. In these models, the arcs could be either pre-existing gaseous structures unrelated to the nuclear activity (e.g. rings or spiral arms), or the post-shock cooling regions of bow shocks driven by the radio ejecta. In this scenario, the outflow has enough power to create shocks and the observed emission-line structures,but not enough power to provide the ionizing radiation (e.g. Whittle et al. 1988; Wilson, Ward & Haniff 1988). An argument in favor of central source photoionization models is the good agreement between the ends of the arcs and the edges of the wedge-shaped ionization structure (see Fig. 3).

**Photon budget:** As we need high spatial resolution data to measure accurately the emission-line fluxes in the arcs, we have used the [O III] fluxes derived from the HST image (see Table. 3), to compute the absolute H$\beta$ luminosity, $\mathcal{L}_{\mathrm{H}\beta}$, of SE1-arc and NW1-arc. Assuming a distance to Mrk 573 of 65 Mpc, and including a reddening correction factor of 2.7 (E(B-V) = 0.3 mag, Tsvetanov & Walsh 1992; extinction curves from Cardelli, Clayton, & Mathis 1989 with $\mathrm{R}_V = 3.1$), we derive absolute [O III] fluxes in the arcs of $2.1 \times 10^{41}$ erg s$^{-1}$ (SE1-arc) and $2.3 \times 10^{41}$ erg s$^{-1}$ (NW1-arc). Using the observed [O III]/ H$\beta$ ratio of $\sim$10.5 , this yields absolute H$\beta$ luminosities $\mathcal{L}_{\mathrm{H}\beta}$ of 2.0 and $2.2 \times 10^{40}$ erg s$^{-1}$ for SE1-arc and NW1-arc, respectively.

Using the case B recombination rates and assuming a temperature of $10^4$ K, the total number of recombinations per second in the arc ($\mathcal{N}_{rec}$) and the total number of ionizing photons reaching the arc per second ($\mathcal{N}_{ion}$), are:

$$\mathcal{N}_{ion}\ \left[\mathrm{photon\ s^{-1}}\right]\ =\ \mathcal{N}_{rec}\ \left[\mathrm{recombination\ s^{-1}}\right]\ =\ 2.09\ \times\ 10^{12}\ \mathcal{L}_{\mathrm{H}\beta}\ \left[\mathrm{erg\ s^{-1}}\right] \tag{1}$$

For a nuclear source, the ionizing photon flux, $\mathcal{F}_{ion}$, at the radius of the arc is then:

$$\mathcal{F}_{ion}\ \left[\mathrm{photon\ s^{-1}\,cm^{-2}}\right]\ =\ 2.09\ \ 10^{12}\ \frac{\mathcal{L}_{\mathrm{H}\beta}\ \left[\mathrm{erg\ s^{-1}}\right]}{4\pi R^2\ \left[\mathrm{cm^2}\right]}\ \left(\frac{\Omega\ [\mathrm{sr}]}{4\pi}\right)^{-1}\ \varepsilon^{-1} \tag{2}$$

where $R$ is the radius of the arc, $\Omega$ is the solid angle subtended by the arc, as seen from the nucleus, and $\varepsilon$ the covering factor of the arc material. Assuming that the direction of nuclear ejection lies in the plane of the sky[7], and that the arcs are circular 'bow shocks' viewed edge-on, this equation gives ionizing photon fluxes, $\mathcal{F}_{ion}$, at the location of the arcs of $2 \times 10^{10}\ \varepsilon^{-1}$ photons cm$^{-2}$ s$^{-1}$ and $1.6 \times 10^{10}\ \varepsilon^{-1}$ photons cm$^{-2}$ s$^{-1}$ for SE1-arc ($R = 1''\!.8 = 570$ pc, $\Omega/4\pi = 0.054$) and NW1-arc ($R = 2''\!.3 = 725$ pc, $\Omega/4\pi = 0.047$), respectively.

**Ionization parameter:** In order to estimate the ionization parameter of the gas in SE1-arc and NW1-arc from the observed [N II]$\lambda$6583/H$\alpha$ and [S II]$\lambda\lambda$6717,6731/H$\alpha$ line ratios, we have used Mappings Ic (see Appendix A in Ferruit et al. 1997a) to compute a sequence of simple photoionization models with ionization parameters U (defined in equation (3) below) varying between $10^{-4}$ and 1. All the models involved a plane-parallel, radiation-bounded slab of gas with constant density (500 cm$^{-3}$) and solar abundances, which is photoionized by an AGN-type central source. The spectrum of the ionizing radiation has been modelled as a broken power-law ($\mathrm{f}_\nu \propto \nu^\alpha$) with different values of $\alpha$ at the low and high energies. For energies

[7]Otherwise, $\mathcal{F}_{ion}$ in equation (2) would have to be multiplied by $\cos^2(\theta)$, where $\theta$ is the angle between the direction of ejection and the plane of the sky.

$< 50$ eV, we have used the spectral index $\alpha = -0.9$ measured by Kinney et al. 1991) from an IUE spectrum of Mrk 573. For energies $> 50$ eV, we have used a steeper power-law with $\alpha = -2$, corresponding to a rough average of the set of model-dependent values of $\alpha$ derived by Turner, Urry, & Mushotzky (1993, typical photon index $\Gamma = 3 = 1 - \alpha$) from ROSAT/PSPC observations of Mrk 573 in the 0.1-2.0 keV band. The [N II]$\lambda$6583/H$\alpha$, [S II]$\lambda\lambda$6717,6731/H$\alpha$ and [O I]$\lambda$6300/H$\alpha$ line ratios inferred from these models for $10^{-4} <$ U $< 1$ are shown in Fig. 16. For SE1-arc and NW1-arc, the line ratios are [N II]/H$\alpha \sim 1$ and [S II]/H$\alpha \sim$ 0.65 (see Table 3 and Fig. 15), which implies ionization parameters of $9 \times 10^{-4}$ and $5 \times 10^{-4}$, respectively.

The ionizing photon flux ($\mathcal{F}_{ion}$) at the location of SE1-arc and NW1-arc can be expressed as a function of the ionization parameter U and the gas density $N_H$:

$$\mathcal{F}_{ion}\left[\mathrm{photon\ s^{-1}\,cm^{-2}}\right] = \mathrm{c}\left[\mathrm{cm\ s^{-1}}\right]\ \mathrm{U}\ \mathrm{N_H}\left[\mathrm{cm^{-3}}\right] \tag{3}$$

where c is the speed of light. Using the values of U determined above and the measured electron densities (Table 3 and Fig. 15), this equation gives ionizing photon fluxes of 1.3–2.2 $\times 10^{10}$ photons cm$^{-2}$ s$^{-1}$ (SE1-arc, U = 5–9 $\times 10^{-4}$, $N_H$ = 850 cm$^{-3}$) and 0.9-1.5 $\times 10^{10}$ photons cm$^{-2}$ s$^{-1}$ (NW1-arc, U = 5–9 $\times 10^{-4}$, $N_H$ = 580 cm$^{-3}$), in good agreement with the values of $\mathcal{F}_{ion}$ derived from the absolute H$\beta$ luminosities of the arcs ($2 \times 10^{10}\ \varepsilon^{-1}$ and $1.6 \times 10^{10}\ \varepsilon^{-1}$ photons cm$^{-2}$ s$^{-1}$ for SE1-arc and NW1-arc, respectively, see previous section). Under the assumption of central source photoionization, this implies that the arc-like features have a covering factor $\varepsilon \sim 1$, i.e. they absorb all or most of the ionizing photons incident on them, only a small fraction of the area of the putative 'bow shocks', as seen from the nucleus, containing low density 'holes' which are porous to ionizing radiation.

According to the MB-IB models of Binette et al. (1996), changes in the [N II]/H$\alpha$ and [S II]/H$\alpha$ ratios could be a result of changes in the ratio of the solid angle subtended by MB clouds to the solid angle subtended by IB clouds ($A_{M/I}$), rather than the ionization parameter as assumed in our calculations. However, in the MB-IB models, any $A_{M/I}$-sequence is accompanied by changes in the He II/H$\beta$ ratio, contrary to what happens for a U-sequence (see Fig. 7 in Binette et al. 1996). In Mrk 573, the nuclear/circumnuclear and external regions have very similar He II/H$\beta$ ratios (see Fig. 7, open circles in Binette et al. 1996), indicating that the changes in line ratios actually reflect changes in the ionization parameter, and not in $A_{M/I}$, supporting our interpretation.

**Bow shock models of the inner arcs:** A possible description of the inner arcs is provided by the geometrically thin bow shock models developed by Taylor, Dyson, & Axon (1992) and Ferruit et al. (1997a). These models assume that the thin arcs generated by the bow shocks are photoionized by nuclear radiation and are transparent to this radiation. To test if the observed properties of the inner arcs could be reproduced using the bow shock models of Ferruit et al. (1997a), we have computed a grid of bow shock models, manually adjusting the input parameters to try to find the best match to the observed spectral characteristics (line ratios and absolute fluxes) of the arcs. Following the same procedure as used for NGC 5929 (Ferruit et al. 1997b), we have first set the geometrical input parameters ($D_Z$ and C, see Ferruit et al. 1997a), but this time using the [O III] image as a reference. In Fig. 3, the lateral and longitudinal (along the jet axis) extents of the arcs are 1.″5 (∼470 pc) and 0.″5 (∼160 pc), respectively for SE1-arc, and 1.″7 (∼530 pc) and 0.″8 (∼250 pc), respectively for NW1-arc. These geometries have been reproduced by using values of $D_Z$ (the distance from the shock apex along the jet axis at which this distance is equal to the radius r of the bow shock) of 290 pc (SE1-arc) and 360 pc (NW1-arc) and setting C = 1 ($Z \propto r^2$ bow shock profile, see Ferruit et al. 1997a).

As for the photoionization models (see Sect. 4.2.2), the spectrum of the nuclear ionizing source has been modelled by a broken power-law ($f_\nu \propto \nu^\alpha$) with $\alpha = -0.9$ for energies $< 50$ eV, and $-2$ for energies $> 50$ eV. Additional ionizing radiation generated 'in situ' by hot shocked gas has not been included (see Sect. 4.5.2 in Ferruit et al. 1997a).

We have included in the model only the emission from the observed arcs. The ends of the arcs (i.e. the 'tails' of the bow shocks in this interpretation) are observed to correspond roughly to the edges of the wedge shaped ionization structure (Fig. 3). In those 'tails', the fluxes of emission-lines like [O III] or [N II] and H$\alpha$ are dominated by emission from the cool, dense photoionized post-shock gas (see Fig. 11b in Ferruit et al. 1997a). Thus, in the adopted case of central source photoionization of the bow shock, the absence of line emission outside the observed arcs is best explained by a dearth of nuclear ionizing photons, with the gas at large distance from the jet axis flowing outside of the ionization cone.

A grid of bow shock models was then constructed by varying the shock velocity, the pre-shock density, the magnetic parameter and the pre-shock ionization parameter. We have not been able to reproduce simultaneously the observed strengths of medium excitation lines like [O III] and those of low excitation lines like [O II], [N II], [S II] and especially [O I] ([O I]$\lambda$6300/H$\alpha \sim 0.13$, Tsvetanov & Walsh 1992). This is a direct consequence of the relative locations of the low and medium excitation photoionization regions in the bow shock models. In the evolutionary track of a gas cell, the low ionization parameter region (in which the low excitation lines are emitted) starts immediately after the particle catastrophic cooling, where the gas density is maximum. Then, as the gas flows along the bow shock, its ionization parameter increases slowly as its density decreases, allowing the existence of medium to high excitation ionic species and their emission lines, like [O III]. To obtain the high [O III]/H$\beta$ ratios observed in the inner arcs, the pre-shock density [and/or the ionization parameter] has to be low [high] enough for the medium excitation regions to exist before the truncation imposed by the observed geometry of the arcs. This cannot be done without weakening the low excitation lines to levels inconsistent with the observations. Therefore, the bow shock model, as it stands in Ferruit et al. (1997a), fails to reproduce the observed line ratios.

The models of Ferruit et al. (1997a) assume the cool post-shock gas is transparent to the ionizing radiation of the central source, i.e. the ionization of the gas is matter-bounded. A future development, which could improve the agreement with observations, would be the inclusion of absorption of ionizing radiation in the post-shock gas, i.e. allowing the gas to be ionization-bounded to photons from the central source.

### *4.2.3. Photoionizing shock models of the inner arcs*

Recently, Dopita & Sutherland (1995, 1996) have calculated the emission-line spectra of radiative shock waves with velocities in the range $150 \leq V_S \leq 500$ km s$^{-1}$. In this sub-section, we compare the energetic, spectral and structural properties of these shock + precursor models with those of SE1-arc and NW1-arc.

Using equations (2.2) and (2.4) of Dopita & Sutherland (1995), the total luminosity of the shock + precursor in H$\beta$, $\mathcal{L}_{\mathrm{H}\beta}$ (erg s$^{-1}$), may be expressed in terms of the shock velocity $V_S$, the shock area $\mathcal{A}$, and the pre-shock density $n_0$:

$$\mathcal{L}_{\mathrm{H}\beta} = \left[7.44 \times 10^{-6} \left(\frac{V_S}{100\ \mathrm{km\ s^{-1}}}\right)^{2.41} + 9.85 \times 10^{-6} \left(\frac{V_S}{100\ \mathrm{km\ s^{-1}}}\right)^{2.28}\right] \left(\frac{n_0}{\mathrm{cm^{-3}}}\right) \left(\frac{\mathcal{A}}{\mathrm{cm^2}}\right) \qquad (4)$$

Assuming that the SE1-arc and NW1-arc features represent bow shocks viewed edge-on and that their line of sight depths are equal to their extents in the plane of the sky (cylindrically symmetric bow shocks), we can use the bow shock geometrical parameters derived in Sect. 4.2.2 to estimate the shock areas of these two arcs. This yields shock areas of $\mathcal{A}_{\rm SE1\text{-}arc}$ = 0.24 kpc$^2$ and $\mathcal{A}_{\rm NW1\text{-}arc}$ = 0.38 kpc$^2$, similar to the geometric areas used in Sect. 4.2.2. For the parameters needed to power the line emission from the arcs (n$_0$ > 10 cm$^{-3}$, V$_S$ ~ 500 km s$^{-1}$, see below), the cooling length $\mathcal{L}_{\rm cool}$ = 1.4 × 10$^{-9}$ V$_S$$^4$ n$_o^{-1}$ pc (where V$_S$ is in km s$^{-1}$ and n$_0$ in cm$^{-3}$, Whittle et al. 1986) < 9 pc, much smaller than the spatial resolution of the HST images, justifying our use of the emission-line images to estimate the shock area.

Next, to derive estimates of the pre-shock densities, we have computed the shock compression factors appropriate to the [S II]-emitting zone. These factors were derived from the [S II] line ratios listed for the grids of models of Dopita & Sutherland (1996, their Tables 8 and 10), for various combinations of reasonable shock velocities (V$_S$ = 200, 300, 400 and 500 km s$^{-1}$) and magnetic parameters (B$_0$/n$_0$$^{1/2}$ = 0, 1, 2 and 4 $\mu$G cm$^{3/2}$). Given the densities of 850 cm$^{-3}$ (SE1-arc) and 580 cm$^{-3}$ (NW1-arc) inferred from the observed [S II] ratio (see Table 3), we have used these compression factors to build a table of pre-shock densities as a function of the shock velocity and magnetic parameter for SE1-arc and NW1-arc. The results are tabulated in Table 4 and have been used, together with the shock areas $\mathcal{A}_{\rm SE1\text{-}arc}$ and $\mathcal{A}_{\rm NW1\text{-}arc}$, to compute the corresponding H$\beta$ luminosities of SE1-arc and NW1-arc predicted by the photoionizing shock models (see Table 5).

Absolute H$\beta$ luminosities comparable to the observed ones (20 and 22 × 10$^{39}$ erg s$^{-1}$ for SE1-arc and NW1-arc, respectively, see Sect. 4.2.2) can only be produced by the combination of high shock velocities (400-500 km s$^{-1}$), high pre-shock densities (> 10 cm$^{-3}$) and high magnetic parameter (2-4 $\mu$G cm$^{3/2}$). The same range of velocities is suggested by the observed [O III]$\lambda$5007/H$\beta$ ratio (~10–11) which can only be produced in shocks with velocities between 400 and 500 km s$^{-1}$ (for solar abundances). Therefore, in the following we will consider only shock velocities, pre-shock densities and magnetic parameters in these ranges.

A first problem with these models is the lack of kinematic perturbations at the locations of SE1-arc and NW1-arc in our velocity and line width maps of [N II]$\lambda\lambda$6548,6583, H$\alpha$ and [S II]$\lambda\lambda$6717,6731 (Fig. 11 and 13). In models with shock velocities of 400-500 km s$^{-1}$ and magnetic parameters of 2-4 $\mu$G cm$^{3/2}$, about ~50 % of H$\alpha$, ~94 % of [N II]$\lambda\lambda$6548,6583 and ~93 % of [S II]$\lambda\lambda$6717,6731 come from the shock region and should therefore exhibit broadened line profiles relative to the [O III]$\lambda$5007 line, more than ~80 % of which comes from the kinematically quiescent precursor. This extra broadening of the low excitation lines is not seen in our observations (see Table 3). In fact, the opposite effect is seen in NW1-arc, where the [N II], H$\alpha$ and [S II] lines are *narrower* than the [O III] line (see Table. 3).

Another problem comes from the spatial extent of the precursor. Equation (4.3) in Dopita & Sutherland (1996) gives the extent of the Strömgren region of the precursor, yielding lengths of $\mathcal{L}$ = 610 × 1/n$_0$ pc (V$_S$ = 400 km s$^{-1}$), where n$_0$ is the pre-shock density in cm$^{-3}$. Given our estimates of the pre-shock densities in the arcs (8-20 cm$^{-3}$ and 5-13 cm$^{-3}$ for SE1-arc and NW1-arc, respectively, see Table 4) and for this conservative shock velocity of 400 km s$^{-1}$ (the extent of the precursor has to be multiplied by a factor of 2 for a 500 km s$^{-1}$ shock), this yields typical extents of 30-80 pc (SE1-arc) and 50-120 pc (NW1-arc) for the H II region of the precursor, which corresponds roughly to the extent of the [O III] zone (see Fig. 4d in Dopita & Sutherland 1996). Thus, the [O III]-emitting region should be at least partially resolved in the HST observations, whereas the arcs are not transversally resolved in our [O III] WFC image (30 pc per pixel), and probably not in the [O III] FOC image (30 pc resolution) of Capetti et al. (1996, the arcs are termed ‘narrow’). Furthermore, the [O II]$\lambda$3727 emission comes partly from the partially ionized region of the precursor and partly from the post-shock region. Given that these two regions are, respectively, upstream of the precursor H II region and downstream of the shock (see Fig. 4d in Dopita & Sutherland

1996), a clear split of the arcs should be seen in the [O II] HST images, with the [O III] arcs lying inbetween. In contrast, the observations by Capetti et al. (1996, see their Fig. 1) show that the structures of NW1-arc in [O II]$\lambda$3727 and [O III]$\lambda\lambda$4959,5007 are almost identical. Any systematic shift between the arcs in these two lines is $< 0\farcs05$ (17 pc), in contradiction to the predictions of the model. Projection effects will tend to create transversely extended [O II] arcs, still in disagreement with the observations.

These considerations rule out a description of the arcs as photoionizing radiative shocks. This kind of model will always require the existence of a photoionized precursor to produce the high [O III]/H$\beta$ ratios observed in the arcs, and will suffer from the problems described in the previous paragraph. We conclude that, if the inner arcs are shock features, the shock velocity must be low ($<$ 300 km s$^{-1}$, to prevent line widths in excess of those observed and the formation of a spatially resolved precursor) and the ionizing photons must be provided by an external source, such as the nucleus.

## 4.3. The outer arcs and the origin of the ionizing photons

### *4.3.1. General considerations*

Our observations clearly show that the second pair of arcs (SE2-arc and NW2-arc) marks the transition between the denser, high-velocity dispersion NLR ([O III] FWHM $>$ 200 km s$^{-1}$), and the more rarefied, lower velocity dispersion ENLR of Mrk 573. These two arcs have a lower gas density and narrower lines than the gas in the NLR (Table 3), but larger densities and broader lines ([O III] FWHM of 120-150 km s$^{-1}$) than the ENLR gas ([O III] FWHM $<$ 45 km s$^{-1}$, Unger et al. 1987). They seem to participate in the ambient velocity field, as does the ENLR gas (Unger et al. 1987; Whittle et al. 1988; Durret & Warin 1990; Tsvetanov & Walsh 1992), although they have a steeper velocity gradient than measured from regions further out (Durret & Warrin 1990; see Sect. 3.2.1).

It is tempting to infer a common origin for the inner and outer arcs, such as bow shocks driven by a jet. However, the increasing distortion of the arcs from bow shock shapes with increasing radius (Fig. 4 and 5; see also Pogge & De Robertis 1995), and their kinematics indicate that SE2-arc and NW2-arc are significantly affected by rotational shearing of the gas (Pogge & De Robertis 1995). These two outer arcs also have lower densities than SE1-arc and NW1-arc (see Table 3), as well as a much more diffuse, filamentary morphology (see Fig. 4 and 5). All this suggests that, even though the outer arcs may share a similar origin with the inner arcs (shocks driven by an intermittent nuclear outflow?), they are less prominent due to a lower pre-shock density and are currently merging with the ambient interstellar medium.

Capetti et al. (1996) have suggested that this filamentary structure of the outer arcs, as well as the absence (or faintness[8]) of associated radio emission could correspond to the rapid expansion of a radio lobe associated with a sudden drop in interstellar gas density, as inferred in IRAS 04210+040 (Holloway et al. 1996). However, we do not observe the high velocities and large broadening of the lines expected in this case. The observations suggest a much less violent process, involving a progressive weakening of the nuclear outflow and the associated shocks with increasing distance from the nucleus.

[8]Falcke et al. (1998) claim the detection of very faint radio emission associated with the outer arcs in their tapered 3.5 cm map.

#### *4.3.2. Viability of a central source photoionization model*

The outer arcs (SE2-arc and NW2-arc) have higher [O III]/[O II] and [O III]/H$\alpha$ ratios than the inner arcs (SE1-arc and NW1-arc). Combining this result with the gas densities inferred by Tsvetanov & Walsh (1992), Capetti et al. (1996) have argued that a local source of ionization is required to explain the ionization structure of Mrk 573. However, this comparison depends on reddening-sensitive line ratios and a combination of line ratios and density measurements obtained from observations with very different spatial resolutions. A more complete study can be conducted using our original (not deconvolved) R configuration data set ([N II]+H$\alpha$+[S II]), which provides homogeneous measurements of line ratios which are sensitive to the ionization parameter U, but insensitive to reddening ([N II]$\lambda$6583/H$\alpha$ and [S II]$\lambda\lambda$6717,6731/H$\alpha$), and of the gas density (as derived from the [S II] ratio) with a much better spatial coverage and resolution than what previously obtained by Tsvetanov & Walsh (1992).

We have therefore used the simple photoionization models described in Sect. 4.2.2 (see also Fig. 16) to convert the observed maps of the [N II]$\lambda$6583/H$\alpha$ and [S II]$\lambda\lambda$6717,6731/H$\alpha$ ratios (original maps, i.e. not deconvolved) into maps of the ionization parameter U. The resulting map of U derived from the [N II]/H$\alpha$ ratio and the dependence of U on distance from the nucleus are shown in Fig. 17 (upper left and upper right panels, respectively). At a given radius, the ionization parameter derived from the [N II]/H$\alpha$ ratio is systematically higher than the ionization parameter obtained using the [S II]/H$\alpha$ ratio, indicating that the simple photoionization models used to derive U are not a very accurate description of the actual situation. The [S II]/H$\alpha$ ratio, in particular, is also sensitive to the precise density used in the models, due to collisional deexcitation of the $^2D_{3/2}$ and $^2D_{5/2}$ levels of S II. However, the two distributions show a similar behavior as a function of radius. As the [N II]/H$\alpha$ ratios have a better signal to noise ratio than the [S II]/H$\alpha$ ratios and are unlikely to be affected by collisional deexcitation (except perhaps in the unresolved nucleus), only the ionization parameters derived from the [N II]/H$\alpha$ ratios will be used in the following analysis.

As clearly apparent in Fig. 17 (upper panels), the ionization parameter displays a minimum at the locations of SE1-arc and NW1-arc, before increasing further out in SE2-arc and NW2-arc. The ionization parameter in NW2-arc displays a strong asymmetry, higher values of U being observed in the southern part of the arc (Fig. 17, upper left). The same asymmetry is seen in the [O III]/(H$\alpha$+[N II]$\lambda$6583) map derived from our HST observations (Fig. 3, bottom left panel). There is also an area of lower U at the north-end of NW1-arc. However, the range of U along the NW1-arc is only a factor of $\sim$1.5.

As each point in Fig. 17, upper right panel, was obtained from a spectrum which also provides a measurement of the density, we have computed for each point the ionizing photon flux, $\mathcal{F}_{ion}$, using equation (3). The resulting dependence of $\mathcal{F}_{ion}$ on radius is shown in Fig. 17 (lower left). Locations where the observed [S II] ratio is consistent with the low density limit are indicated in light red or light blue. For these points, the actual density could be much lower than the nominal estimate, and we would overestimate $\mathcal{F}_{ion}$ in our calculation. Points within 0.″5 of the nucleus (gray rectangle in the figure) are also subject to uncertainty as they can be affected by (spatial) resolution and collisional deexcitation effects. We find that $\mathcal{F}_{ion}$ decreases with increasing projected radius from the nucleus, up to a radius of $\sim$2.″5. Beyond that, there is a wide spread of $\mathcal{F}_{ion}$ at a given radius, but most of the density information at these radii comes from [S II] line ratios consistent with the low density limit.

We have then computed, for each point, the rate of emission of ionizing photons, $\mathcal{Q}_{ion}$, by a central compact source which corresponds to the measured photon flux, $\mathcal{F}_{ion}$. For a given deprojected radius R, and assuming that the nuclear ionizing radiation does not suffer any absorption on its way from the nucleus, we have:

$$\mathcal{Q}_{ion}\ \left[\text{photon s}^{-1}\right]\ =\ 4\pi\ (\text{R}\ [\,\text{cm}\,])^2\ \mathcal{F}_{ion}\ \left[\text{photon s}^{-1}\,\text{cm}^{-2}\,\right] \tag{5}$$

Assuming that the emission-line region lies in the plane of the sky and using equation (3), $\mathcal{Q}_{ion}$ becomes:

$$\mathcal{Q}_{ion}\ \left[\text{photon s}^{-1}\right]\ =\ 3.6\ \times\ 10^{53}\ \ (\text{r}\ [\,''\,])^2\ \text{U}\ \text{N}_\text{H}\ \left[\text{cm}^{-3}\,\right] \tag{6}$$

The resulting dependence of $\mathcal{Q}_{ion}$ on r is shown in Fig. 17 (right panel). As for $\mathcal{F}_{ion}$, the estimates of $\mathcal{Q}_{ion}$ in the inner 0.″5 region (grey rectangle) are not reliable and should be treated with caution.

If the central ionizing source has not varied[9], $\mathcal{Q}_{ion}$ must be constant, or decrease with increasing radius if there is any absorption of the nuclear radiation on its way to the outer parts of the emission-line nebulosities. Instead, $\mathcal{Q}_{ion}$ increases by more than one order of magnitude between the central regions and the outer arcs 4″ away from the nucleus (Fig. 17, lower right panel). This indicates that a non-variable, central source photoionization model is not viable in Mrk 573. An additional, extra-nuclear source of ionizing photons is required to explain the observed ionization and excitation structure of the emission-line region, in agreement with the conclusions of Capetti et al. (1996). Judging by the increase of $\mathcal{Q}_{ion}$ in the inner 2″, such extra ionizing photons appear to be required in SE1-arc and NW1-arc.

#### *4.3.3. Are the additional ionizing photons generated by hot stars ?*

Recently, González-Delgado et al. (1998) have provided direct evidence for the existence of nuclear starbursts in three Seyfert 2 galaxies and shown that they account for the ‘featureless continuum’ component called FC2. An extended, diffuse excess of near-UV (3600 Å) light is detected in Mrk 573 at the locations of the outer arcs (see Fig. 3 in Pogge & De Robertis 1993) and could be interpreted in terms of a starburst in the vicinity of the outer arcs. The hot stars in such a starburst could provide the required, spatially extended source of ionizing photons. However, between 1″ and 3″-4″, $\mathcal{Q}_{ion}$ increases by almost a factor 10 (Fig. 17, bottom right panel) indicating that, in this interpretation, hot stars would be the dominant source of ionizing photons at the locations of the outer arcs. SE2-arc and NW2-arc should therefore exhibit line ratios typical of H II regions, in contradiction with the observations which show that they display Seyfert-like line ratios. Therefore, hot stars are probably not the spatially extended source of ionizing photons.

#### *4.3.4. Are the additional ionizing photons generated by shocks ?*

In the last sections, we argued that a central source photoionization model cannot account for the ionization structure of the emission-line region of Mrk 573 and showed that the extended source of ionizing photons is probably not hot stars. In the AGN context, the second plausible candidate for the generation of an extended source of ionizing photons is fast shocks, presumably generated by the propagation of the radio ejecta through the insterstellar medium of Mrk 573. The procedure used to check if photoionizing shocks can power the line emission in SE1-arc and NW1-arc (see Sect. 4.2.3) cannot be safely applied to SE2-arc and NW2-arc, which arcs are ill-defined (especially NW2-arc) and the [S II] ratio is too close to its low density limit to provide reliable estimates of the density.

[9]The dependence of $\mathcal{Q}_{ion}$ on radius could be explained if the nuclear ionizing flux has decreased by more than a factor 10 in the last 4,000 years.

However, as for the inner arcs, any shock+precursor structure should display distinctive morphological signatures in the high spatial resolution HST [O III], [O II] and H$\alpha$+[N II] images. The observed [O III]$\lambda$5007/H$\beta$ ratio of $\sim$10 (see Fig. 15) yields typical shock velocities higher than 400 km s$^{-1}$ (for solar abundances). In addition, an upper limit to the pre-shock density of 5 cm$^{-3}$ is obtained using the minimum expected compression factor of $\sim$46 in the [S II] emitting zone (400-500 km s$^{-1}$ shock with a magnetic parameter of 0-4 $\mu$G cm$^{3/2}$, Dopita & Sutherland 1996; see Sect. 4.2.3), and the density of 200 cm$^{-3}$ obtained by Tsvetanov & Walsh (1992, their Fig. 7) 4$''$ away from the nucleus as an upper-limit on the (post-shock) density in the outer arcs. Treating the shock velocity of 400 km s$^{-1}$ as a lower limit, and using this upper limit on pre-shock density, we can derive a lower limit to the size of the precursor H II region, which is $\mathcal{L}$ = 610 $\times$ 1/n$_0$ pc (Dopita & Sutherland 1996). This gives a minimum extent for the H II region of the precursor (where roughly 90 % of the total [O III] flux of the shock+precursor structure is emitted) of 120 pc (0$''$.4). Therefore, as in the case of SE1-arc and NW1-arc (see Sect. 4.2.3), the outer arcs should display strong morphological differences between images in [O III] and lower excitation lines like H$\alpha$, [O II] and [N II]. This is not the case (see our Fig. 3 and Fig. 1 in Capetti et al. 1996). We thus conclude that photoionizing radiative shocks are ruled out for both the inner and outer arcs of Mrk 573.

The remaining possibility is that the spatially extended source of ionizing photons is faster shocks located in the vicinity of the arcs, but not directly associated with them. Such shocks could correspond to the jet/cloud interactions suspected to take place in the strings of knots (SE2-knots, SE1-knots and NW1-knots, see Sect. 4.2.1). In the inner regions, where the density is high enough for these fast shocks to be radiative, and for their internal structure to be spatially unresolved even at HST resolution, they show up in the HST emission-line images as strings of kinematically disturbed emission-line knots (SE1-knots, NW1-knots and in a lesser extent SE2-knots). However, no emission-line signature of such shocks is seen near NW2-arc, neither in the HST images, nor in our spectroscopic data. Therefore, in the vicinity of NW2-arc, any shock producing the ionizing photons must be fast enough and/or propagating in a sufficiently low density medium to be non-radiative, i.e. for the shocked gas not to cool down to temperatures where it would emit strong optical lines. These shocks will have extended photoionized precursors, which will certainly have a low surface brightness and may not be detected in the emission-line images, except in regions of enhanced density such as NW2-arc. For the shock to be non-radiative, the cooling length $\mathcal{L}_{\rm cool}$ must be larger than the distance between the outer arcs and the nucleus ($\sim$4$''$, i.e. $\sim$1.3 kpc). Assuming a pre-shock density of 1 cm$^{-3}$ and using the equation for $\mathcal{L}_{\rm cool}$ given in Sect. 4.2.3, we find a minimum shock velocity of 1000 km s$^{-1}$. High shock velocities are also necessary to produce the ionizing photon fluxes of $\mathcal{F}_{ion}$ $\sim$ 10$^{10}$ photons cm$^{-2}$ s$^{-1}$ seen by the gas in SE2-arc and NW2-arc (Fig. 17, bottom left panel), as a 500 km s$^{-1}$ shock propagating into a 1 cm$^{-3}$ medium produces a ionizing flux of only 2.4 $\times$ 10$^9$ photons cm$^{-2}$ s$^{-1}$, even before any geometrical dilution or absorption is taken into account. We envisage the jet as progressively weakening through such interactions, so the bow shock at the end of the jet, identified with the arcs, is of relatively low velocity.

## 5. Summary and conclusion

We have reported the results of observations of the emission-line region of Mrk 573 with the WFPC2/HST in the [O III] and H$\alpha$+[N II] emission-lines as well as with the 3D spectrograph TIGER in the H$\beta$+[O III] and H$\alpha$+[N II]+[S II] wavelength domains. The HST [O III]/(H$\alpha$+[N II]$\lambda$6583) line ratio image shows a well defined bi-cone. The central nucleus and the various arcs and knots seen in the HST emission-line images are shown to exhibit very different kinematical and spectral behaviors. The results for each component can be summarized as follow:

• *The nucleus:* The velocity of the central [O III] peak is in very good agreement with the stellar systemic velocity. The absence of clear kinematical signatures of shocks (no velocity shift and relatively narrow lines) suggests that the gas is probably photoionized by the active nucleus.
• *The strings of knots:* Strong velocity perturbations are found in the strings of knots, in the vicinity of each radio component, and are interpreted as signatures of the interaction/deflection of the radio jet with/by individual clouds.
• *The inner arcs:* We have ruled out the notion that the line emissions of the inner arcs (SE1-arc and NW1-arc, see Fig. 5) represent photoionizing ('autoionizing') shocks, as modelled by (Dopita & Sutherland 1995, 1996), by a comparison of the predicted and observed morphological and spectral properties. Specifically, the arcs have a similar morphological structure in the medium excitation [O III]$\lambda$5007 line as in low excitation lines such as [O II]$\lambda$3727 and [N II]$\lambda\lambda$6548,6583. This similarity is not expected in the photoionizing shock model, in which most of the [O III]$\lambda$5007 emission comes from the precursor and most of the low excitation line emission comes from the post-shock gas. Further, the expected kinematic structure of the shock is not seen. These arcs are therefore photoionized by an external source. We find good agreement between the ionizing photon fluxes inferred from the absolute H$\beta$ luminosity and from the observed ionization parameter and gas density, indicating that in the frame of a central source photoionization model, the covering factor of the material of the inner arcs is close to unity. The bow shock models of Ferruit et al. (1997a) with central source photoionization fail to reproduce the observed line ratios, possibly because they assume that the ionization of the cool post-shock gas is matter-bounded.
• *The outer arcs:* SE2-arc and NW2-arc (see Fig. 5) are shown to mark the transition between the NLR and ENLR gas in Mrk 573 and could represent shock structures similar to the inner arcs, but which are currently dissipating.

From the spatial variation of the ionization parameter and gas density and assuming that the compact central source of ionizing photons has not varied in the last 4000 years, we show that this central source alone cannot account for the ionization of the outer arcs and may account only partially for the ionization of the inner arcs. The spectra of the outer arcs are Seyfert-like, suggesting that hot stars cannot be the spatially extended source of ionizing photons. As in the case of the inner arcs, photoionizing radiative shocks fail to explain the spectral and morphological properties of the outer arcs and cannot be the source of the additional ionizing photons. Alternatively, the ionizing photons could be supplied by fast shocks located in the vicinity of the arcs but separate from them. These shocks would be radiative in the dense inner regions, their presence suggested by the emission-line knots associated with the radio ejecta, and non-radiative in the low density outer regions where they could supply the ionizing photons without being seen in the optical and, therefore, without suffering the morphological and spectral problems described above.

This high-spatial resolution work constitutes one of the most extensive studies of the circumnuclear ionized gas in a Seyfert galaxy to date. In the future, STIS spectrographic observations combining the high-spatial resolution of HST with an extensive UV-optical coverage (and ideally a good spatial coverage by using multiple slit positions and slitless spectroscopy) will be a key to confirm and strengthen our results and to investigate in detail the origin of the ionizing photons.

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Table 1: Log file of the TIGER spectrographic exposures in the blue (B) and red (R) spectral configurations. In this table, $\lambda_0$ is the central wavelength, $\Delta\lambda$ the filter bandpass, $\delta\lambda$ the spectral resolution, $\delta v_{\lambda_0}$ the corresponding velocity resolution at $\lambda_0$, and $t_i$ the integration time.

| ID | $\lambda_0/\Delta\lambda$ | $\delta\lambda$ | $\delta v_{\lambda_0}$ | $t_i$ | airmass | Comments |
|---|---|---|---|---|---|---|
| B1 | 5000/400 Å | 3.6 Å | 216 km s$^{-1}$ | 3600 s | 1.006 | [O III]+H$\beta$ configuration, centered east of the nucleus |
| B2 | 5000/400 Å | 3.6 Å | 216 km s$^{-1}$ | 3600 s | 1.102 | [O III]+H$\beta$ configuration, centered west of the nucleus |
| R1 | 6750/400 Å | 3.6 Å | 160 km s$^{-1}$ | 2819 s | 1.092 | [N II]+H$\alpha$+[S II] configuration, centered east of the nucleus |
| R2 | 6750/400 Å | 3.6 Å | 160 km s$^{-1}$ | 2821 s | 1.198 | [N II]+H$\alpha$+[S II] configuration, centered west of the nucleus |

Table 2. [O III] fluxes of the Emission Line Region components in Mrk 573

| Component | Offset arcsec [pc] | Area arcsec$^2$ [kpc$^2$] | [O III] flux erg/sec/cm$^2$ | Relative flux | [O III] / (H$\alpha$+[N II]) |
|---|---|---|---|---|---|
| SE2-arc | 2.9 [910] | 2.6 [0.26] | $1.2 \times 10^{-13}$ | 8% | 2.8–3.5 |
| SE2-knots | 2.5 [790] | 0.42 [0.04] | $0.13 \times 10^{-13}$ | 1% | 2.5 |
| SE1-arc | 1.6 [500] | 1.32 [0.13] | $1.5 \times 10^{-13}$ | 10% | 1.8–2.1 |
| SE1-knots | 0.9 [280] | 0.55 [0.05] | $1.0 \times 10^{-13}$ | 6% | 2–3 |
| Nucleus | 0 [0] | 0.55 [0.05] | $3.5 \times 10^{-13}$ | 24% | 2.7–2.9 |
| NW1-knots | 0.7 [220] | 0.63 [0.06] | $0.7 \times 10^{-13}$ | 5% | 1.9–2.2 |
| NW1-arc | 1.6 [500] | 1.84 [0.18] | $1.7 \times 10^{-13}$ | 12% | 1.5–1.7 |
| NW2-arc | 3.6 [1130] | 2.28 [0.23] | $0.7 \times 10^{-13}$ | 5% | 1.8–3.5 |
| Total | | | $1.5 \cdot 10^{-12}$ | 100% | |

Note. — (1) – Designation of component, (2) – Projected radial distance from nucleus, (3) – Area of component, (4) – [O III]$\lambda$5007 flux, (5) – [O III]$\lambda$5007 flux as percentage of total [O III] flux, (6) – Range of [O III]/(H$\alpha$+[N II]) ratio

Table 3: Results of single Gaussian fitting of spectra averaged over selected 0.″2 diameter areas in each of the deconvolved data cubes (see Fig. 7 for their locations in Mrk 573). All the spectra are displayed in Fig. 8, 10, 12 and 14. The spatial resolution is different for the different deconvolved data cubes. The parameters of the weak lines H$\beta$ and [S II] (see Fig. 10 and 14) at SE2-red, SE1-red and NW1-blue are not reliable and should be treated with caution.

| | | SE2-arc | SE2-red | SE1-arc | SE1-red |
|---|---|---|---|---|---|
| Location | $\Delta\alpha$ ($''$ [pc]) | -2.8 [-880] | -1.8 [-570] | -1.7 [-530] | -0.6 [-190] |
| | $\Delta\delta$ ($''$ [pc]) | -1.5 [-470] | -1.0 [-310] | -0.6 [-190] | -0.2 [-60] |
| H$\beta$ $\lambda$4861 | (v – 5150)/FWHM (km s$^{-1}$) | -180/150 | -50/unresolved | -60/350 | +135/460 |
| [O III]$\lambda$5007 | (v – 5150)/FWHM (km s$^{-1}$) | **-130/120** | **+30/350** | **-90/290** | **+110/470** |
| H$\alpha$ $\lambda$6563 | (v – 5150)/FWHM (km s$^{-1}$) | -100/90 | -50/260 | -80/340 | +70/430 |
| [N II]$\lambda$6583 | (v – 5150)/FWHM (km s$^{-1}$) | -90/170 | -50/190 | -70/340 | +70/470 |
| [N II]$\lambda$6583/H$\alpha$ | | 0.5 | 0.8 | 1.0 | 0.7 |
| [S II]$\lambda\lambda$6717,6731 | (v – 5150)/FWHM (km s$^{-1}$) | -90/50 | -90/310 | -100/300 | -10/550 |
| [S II]$\lambda$6717/[S II]$\lambda$6731 | | 1.5 | 0.9 | 0.9 | 0.7 |
| Density | (cm$^{-3}$) | < 100 | 850 | 850 | 2000 |
| | | Nucleus | NW1-blue | NW1-arc | NW2-arc |
| Location | $\Delta\alpha$ ($''$ [pc]) | 0 [0] | +0.8 [+250] | +2.1 [+660] | +3.4 [+1070] |
| | $\Delta\delta$ ($''$ [pc]) | 0 [0] | +0.8 [+250] | +0.8 [+250] | +2.2 [+690] |
| H$\beta$ $\lambda$4861 | (v – 5150)/FWHM (km s$^{-1}$) | -10/440 | -230/110 | -20/330 | +90/unresolved |
| [O III]$\lambda$5007 | (v – 5150)/FWHM (km s$^{-1}$) | **-10/350** | **-290/440** | **+40/230** | **+90/150** |
| H$\alpha$ $\lambda$6563 | (v – 5150)/FWHM (km s$^{-1}$) | +20/380 | -250/360 | +60/140 | +100/180 |
| [N II]$\lambda$6583 | (v – 5150)/FWHM (km s$^{-1}$) | +20/360 | -260/400 | +70/160 | +90/240 |
| [N II]$\lambda$6583/H$\alpha$ | | 0.6 | 0.9 | 1.0 | 0.4 |
| [S II]$\lambda\lambda$6717,6731 | (v – 5150)/FWHM (km s$^{-1}$) | +10/330 | -370/540 | +50/140 | +50/150 |
| [S II]$\lambda$6717/[S II]$\lambda$6731 | | 0.6 | 1.3 | 1.0 | 1.3 |
| Density | (cm$^{-3}$) | 3600 | 130 | 580 | 130 |

Table 4: SE1-arc and NW1-arc pre-shock densities ($cm^{-3}$) as a function of the shock velocity (200 km $s^{-1}$< $V_S$ < 500 km $s^{-1}$) and magnetic parameter (0 $\mu$G $cm^{3/2}$ < $B_0/n_0^{1/2}$ < 4 $\mu$G $cm^{3/2}$). See Sect. 4.2.3 for details.

| $B_0/n_0^{1/2}$ ($\mu$G $cm^{3/2}$) | $V_S$ | 200 km $s^{-1}$ | 300 km $s^{-1}$ | 400 km $s^{-1}$ | 500 km $s^{-1}$ |
|---|---|---|---|---|---|
| 0 | SE1-arc | 2.5 | 1.1 | 0.8 | 0.6 |
| | NW1-arc | 1.7 | 0.8 | 0.6 | 0.4 |
| 1 | SE1-arc | 9.7 | 6.8 | 5.1 | 4.2 |
| | NW1-arc | 6.7 | 4.6 | 3.5 | 2.9 |
| 2 | SE1-arc | 15.5 | 12.0 | 8.9 | 7.9 |
| | NW1-arc | 10.5 | 8.2 | 6.0 | 5.4 |
| 4 | SE1-arc | 37.0 | 26.6 | 18.3 | 15.7 |
| | NW1-arc | 25.2 | 18.0 | 12.5 | 10.8 |

Table 5: Predicted SE1-arc and NW1-arc H$\beta$ luminosities ($\mathcal{L}_{\mathrm{H}\beta}$, in units of $10^{39}$ erg s$^{-1}$) as a function of the shock velocity (200 km s$^{-1}$< $V_S$ < 500 km s$^{-1}$) and magnetic parameter (0 $\mu$G cm$^{3/2}$ < $B_0/n_0^{1/2}$ < 4 $\mu$G cm$^{3/2}$). The luminosities are the sum of the contributions of the shock and precursor in the photoionizing shock models of Dopita & Sutherland (1995, 1996)

| | $V_S$ | 200 km s$^{-1}$ | 300 km s$^{-1}$ | 400 km s$^{-1}$ | 500 km s$^{-1}$ |
|---|---|---|---|---|---|
| $B_0/n_0^{1/2}$ ($\mu$G cm$^{3/2}$) | | | | | |
| 0 | SE1-arc | 0.5 | 0.6 | 0.8 | 1.0 |
| | NW1-arc | 0.8 | 0.7 | 1.0 | 1.1 |
| 1 | SE1-arc | 1.9 | 3.5 | 5.1 | 7.1 |
| | NW1-arc | 2.1 | 3.8 | 5.6 | 7.8 |
| 2 | SE1-arc | 3.1 | 6.2 | 8.9 | 13.4 |
| | NW1-arc | 3.4 | 6.7 | 9.6 | 14.6 |
| 4 | SE1-arc | 7.4 | 13.8 | 18.3 | 26.7 |
| | NW1-arc | 8.1 | 14.8 | 20.0 | 29.2 |

Fig. 1.— Synthetic emission-line sky spectrum used in the sky subtraction. The horizontal dashed line marks the 1 $\sigma$ noise level in individual spectra.

Fig. 2.— **Top row:** [O III]$\lambda$5007 intensity (left), centroid velocity (middle) and FWHM (right) maps, as derived from a single component Gaussian fitting of the line in each spectrum of the original (i.e. not deconvolved) [O III] TIGER data cube. **Second row:** As top row, but derived from the [O III] data cube by means of a Richardson-Lucy deconvolution (150 iterations, see Sect. 2.2.3). **Third row:** As top row, but derived from the [O III] data cube by means of a 'weakly guided' deconvolution (150 iterations, $\alpha = 0.1$, see Sect. 2.2.3). **Bottom row:** As top row, but derived from the [O III] data cube by means of a 'strongly guided' deconvolution (150 iterations, $\alpha = 1$, see Sect. 2.2.3).

Fig. 3.— **Top left panel:** Continuum subtracted H$\alpha$+[N II] image of Mrk 573 taken with the Wide Field Camera ($0\farcs0996$ pixels). The intensity scale is proportional to the square root of the brightness. The location of the continuum peak of the galaxy is marked by a cross, and the (B1950) coordinates were obtained as described in Falcke et al. (1998). **Top right panel:** Continuum subtracted [O III]$\lambda$5007 image of Mrk 573 taken with the Wide Field Camera ($0\farcs0996$ pixels). The intensity scale is proportional to the square root of the brightness. **Bottom left panel:** Excitation map of Mrk 573, obtained by dividing the [O III] map by the H$\alpha$+[N II] map. Darker shades represent regions of higher [O III]/(H$\alpha$+[N II]) ratio. The linear grayscale ranges from [O III]/(H$\alpha$+[N II]) = 1 to 5.5. **Bottom right panel:** Broad-band F606W image of Mrk 573 taken with the Planetary Camera ($0\farcs0455$ pixels), overlaid with logarithmic isophotes.

Fig. 4.— Emission-line images of Mrk 573 obtained on the Planetary Camera with broad-band filters (F569W minus F814W, includes emission-lines such as H$\beta$ and [O III]$\lambda\lambda$4959,5007, right panel; F675W minus F814W, includes emission-lines such as [O I]$\lambda\lambda$6300,6364, H$\alpha$, [N II]$\lambda\lambda$6548,6583, and [S II]$\lambda\lambda$6717,6731, left panel; see Sect. 2.1.2). The intensity scale is proportional to the square root of the brightness.

Fig. 5.— The HST continuum-subtracted [O III] image shown in Fig. 3 (upper right panel). The locations and adopted names of the various structures in the emission-line region are indicated.

Fig. 6.— **Top left panel:** [O III] HST map of Mrk 573 with contours of the 2 cm radio map at 0.5, 1 and 1.5 mJy (beam)$^{-1}$ superimposed. **Top right panel:** [O III]$\lambda$5007 intensity map derived from single component Gaussian fitting of the deconvolved TIGER [O III] data cube, with contours of the 3.5 cm radio map at 0.5, 1 and 1.5 mJy (beam)$^{-1}$ superimposed. **Middle left panel:** Superposition of the [O III]$\lambda$5007 intensity (color image) and centroid velocity (contours from 4830 to 5280 km s$^{-1}$ with a 50 km s$^{-1}$ increment) maps. Both were derived from single component Gaussian fitting of the deconvolved TIGER [O III] data cube. **Middle right panel:** [O III]$\lambda$5007 centroid velocity map (color image) derived from single component Gaussian fitting of the deconvolved TIGER [O III] data cube, with contours of the 3.5 cm radio map at 0.5, 1 and 1.5 mJy (beam)$^{-1}$ superimposed. **Bottom panels:** Same as middle panels, but for the FWHM instead of the centroid velocity. Contours from 3 Å to 10 Å, with a 1 Å increment.

Fig. 7.— **Central image:** [O III]$\lambda$5007 emission-line map reconstructed from single component Gaussian fitting of the TIGER deconvolved data cube ('weakly guided' method, 300 iterations), with the [O III] isovelocity contours (see Fig. 6) superimposed. **Profiles:** [O III]$\lambda$5007 velocity profiles from eight selected locations (averaged over $0\farcs2$ diameter circular areas, i.e. over 3-4 spectra of the deconvolved data cube). Properties of the emission-lines at these locations are given in Table 3. The origin corresponds to the stellar systemic velocity of 5150 km s$^{-1}$ (Nelson & Whittle 1995).

Fig. 8.— Continuum subtracted [O III]$\lambda$5007 spectra (thick lines) at eight selected $0\farcs2$ diameter locations

(see Fig. 7 and Table 3) with the fitted Gaussian superimposed (thin lines). The spectra were obtained from the [O III] data cube through 300 iterations of 'weakly guided' deconvolution (see Sect. 2.2.3).

Fig. 9.— H$\beta$ intensity (left), velocity (middle) and FWHM (right) maps derived from a single component Gaussian fitting of each spectrum in the original (i.e. not deconvolved) H$\beta$+[O III]data cube.

Fig. 10.— Continuum subtracted H$\beta$ spectra (thick lines) at selected $0\farcs2$ diameter locations (see Fig. 7 and Table 3) with the fitted Gaussians superimposed (thin lines). The spectra were obtained from B configuration observations processed with 150 iterations of Richardson-Lucy deconvolution (see Sect. 2.2.3).

Fig. 11.— **Top panels:** H$\alpha$ intensity (left), velocity (middle) and FWHM (right) maps as derived from a single component Gaussian fitting of each spectrum in the deconvolved H$\alpha$+[N II] data cube ('weakly guided' deconvolution – 300 iterations). **Bottom panels:** [N II]$\lambda$6583 intensity (left), velocity (middle) and FWHM (right) maps as derived from a single Gaussian fitting of each spectrum in the deconvolved H$\alpha$+[N II] data cube ('weakly guided' deconvolution – 300 iterations).

Fig. 12.— Continuum subtracted [N II]$\lambda\lambda$6548,6583 + H$\alpha$ spectra (thick lines) at selected $0\farcs2$ diameter locations (see Fig. 7 and Table 3) with the fitted Gaussians superimposed (thin lines). The spectra were obtained from the H$\alpha$+[N II] data cube through 300 iterations of 'weakly guided' deconvolution (see Sect. 2.2.3).

Fig. 13.— **Top panels:** [S II]$\lambda$6717 (left) and [S II]$\lambda$6731 (right) intensity maps as derived from single component Gaussian fitting of each spectrum in the original (i.e. not deconvolved) R configuration data cube. **Middle panels:** [S II]$\lambda\lambda$6717,6731 velocity (left) and FWHM (right) as derived from single component Gaussian fitting of each spectrum in the original (i.e. not deconvolved) R configuration data cube. **Bottom panels:** Maps of the density sensitive [S II]$\lambda$6717/[S II]$\lambda$6731 ratio overlaid with the isophotes of the [S II]$\lambda$6717 intensity map (left) and the [S II] isovelocity contours (right). The isovelocity contours range from 5000 to 5250 km s$^{-1}$, with a contour interval of 50 km s$^{-1}$.

Fig. 14.— Continuum subtracted [S II]$\lambda\lambda$6717,6731 spectra (thick lines) at selected $0\farcs2$ diameter locations (see Fig. 7 and Table 3) with the fitted Gaussians superimposed (thin lines). The spectra were obtained from the [S II] data cube processed with 150 iterations of Richardson-Lucy deconvolution (see Sect. 2.2.3).

Fig. 15.— **Top left panel:** Plot of the distribution of the [O III]$\lambda$5007 peak intensity (in $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-2}$) as a function of the projected radial distance from the nucleus. Negative (positive) radii correspond to the southeast (northwest) side of the emission-line region. Secondary peaks in the [O III] intensity are seen at the locations of the two pairs of arcs and are marked. Each point in this plot corresponds to one spectrum in the original (not deconvolved) TIGER data cube. **Top right panel:** The original (not deconvolved) TIGER [O III] image with the various arcs indicated. The line in PA 35° separates the southeast and northwest sides. **Middle (left and right ) and bottom (left) panels:** Plots of the [O III]$\lambda$5007/H$\beta$ (middle left; black crosses – no correction for H$\beta$ absorption; red and blue symbols : corrected for H$\beta$ absorption), [N II]$\lambda$6583/H$\alpha$ (middle right) and [S II]$\lambda\lambda$6717,6731/H$\alpha$ (bottom left) line ratios as a function of the projected radial distance from the nucleus. The positions of individual arcs are labelled. Lines with a fitted intensity peak below 0.4 × $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-2}$ (i.e. $\sim$13 $\sigma$) were omitted from the flux ratio calculations. **Bottom right panel:** Plot of the density, as derived from the [S II]$\lambda$6717/[S II]$\lambda$6731 ratio, as a function of the radial distance from the nucleus. Spectra with a fitted intensity peak in the [S II]$\lambda$6717 or [S II]$\lambda$6731 lines below 0.2 × $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ arcsec$^{-2}$ (i.e. $\sim$7 $\sigma$) were not used to calculate the density. The light red and light blue symbols correspond to density measurements for which

the error bars on the [S II] ratio reach the low density limit of the [S II] ratio.

Fig. 16.— Variation of the [N II]$\lambda$6583/H$\alpha$ (solid line), [S II]$\lambda\lambda$6717,6731/H$\alpha$ (dotted line) and [O I]$\lambda$6300/H$\alpha$ (dashed line) line ratios with the ionization parameter U, as derived from simple plane-parallel photoionization models with Mappings Ic (see Sect. 4.2.2).

Fig. 17.— **Top left panel:** Map of the ionization parameter U, as derived from the [N II]/H$\alpha$ ratio (see Sections 4.2.2 and 4.3.2), with isophotes of the HST [O III] image superimposed. White dots indicate regions where the [S II] ratio is consistent with the low density limit to within the errors. **Top right panel:** Variation of the ionization parameter, U, as a function of the projected radial distance from the nucleus, as derived from [N II]/H$\alpha$ (diamonds) and [S II]/H$\alpha$ (squares). Lines with a fitted peak intensity below $0.4 \times 10^{-15}$ erg $s^{-1}$ $cm^{-2}$ $Å^{-1}$ $arcsec^{-2}$ (i.e. $\sim$13 $\sigma$) are not displayed. **Bottom left panel:** Ionizing photon flux, $\mathcal{F}_{ion}$ (as derived from the [N II]/H$\alpha$ line ratio), as a function of the projected radial distance from the nucleus. Points where, given the error bars, the [S II] ratio is consistent with the low density limit (white dots in the top left panel) are marked with light red or blue diamonds. The gray-shaded rectangle corresponds to the nuclear regions (projected radius $< 0\farcs5$), where there may be a wide range of density, and where our measurements of the density cannot be safely used to estimate $\mathcal{F}_{ion}$. **Bottom right panel:** Plot of the number of ionizing photons, $\mathcal{Q}_{ion}$, emitted per second by a compact central source versus radius.