

# The Narrow Line Region of the Seyfert 2 galaxy Mrk 78. An infrared view

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## ABSTRACT

We report near-infrared spectroscopic data for the Seyfert 2 galaxy Mrk 78, taken with the LIRIS near-infrared camera/spectrometer at the William Herschel Telescope (WHT). The long-slit spectra clearly show extended emission. The resolution and depth of the near-infrared spectra allows the examination of its morphology and ionization regions, and a direct comparison with similarly deep visible spectra. The emission-line ratios obtained are used to derive the extinction towards the nucleus. The detection of strong features such as [Fe II], H<sub>2</sub>, hydrogen recombination lines and the coronal [Si VI] $\lambda$ 1.962 line is used to study the kinematics and excitation mechanisms occurring in Mrk 78, revealing that despite of the strong radio-jet interaction present in this object, photoionization from the active nucleus dominates the narrow line region emission, while UV fluorescence is the source of the H<sub>2</sub> emission. Lines with extended emission yield velocity distributions with an amplitude of about 600 km s<sup>-1</sup>, the consequence of an eastern lobe moving away from us plus a western lobe with the opposite contribution. We used the photoionization code CLOUDY to recreate a typical narrow line region region, to derive the ionization parameter, and to compare our spectral data with diagnostic diagrams.

*Subject headings:* active galactic nuclei — individual Mrk 78 — near infrared

## 1. Introduction

The availability of advanced near-infrared (NIR) instrumentation with panoramic arrays offers the possibility of employing diagnostic techniques that were formerly reserved to optical spectroscopy. Besides, long-slit NIR spectroscopy offers the possibility of characterizing the velocity field in AGN, using different line species from high ionization emission lines (e.g., [Si VI] $\lambda$  1.962  $\mu$ m), H recombination lines, Fe lines (mostly triggered by shocks), molecular H lines, or even stellar absorption features. These constitute a plethora of diagnostic tools that can be used to characterize many of the relevant phenomena acting in AGN,

from the regions close to the actual nucleus, to partially ionized zones, to the borders of molecular clouds, etc. Furthermore, dust extinction is reduced in the IR with respect to the optical range, thus revealing lines whose optical counterparts could be obscured.

The velocity dispersions measured in the narrow emission line region (NLR) of Seyfert galaxies are believed to be governed by the galaxy's gravitational field (Whittle 1992; Nelson & Whittle 1996). However, in a minority of Seyferts, with relatively luminous linear radio sources, there is evidence for significant additional (jet related) acceleration (Ferruit 2002; Veilleux et al. 2002). The interplay between radio-emitting flows and the line-emitting gas is important in the study of active galaxies, especially those with observable radio jets (Cecil et al. 2000, 2002; Ferruit et al. 1999). This interplay can occur in a wide range of circumstances, for instance, radio jets can be disrupted or deflected by the material in the nuclear

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and interstellar media. In turn, the jets can ablate, shock accelerate, or destroy line-emitting clouds, or even trigger bursts of star formation. Mrk 78 is a classical example of an AGN with a jet–gas interaction, showing large bipolar flows (Whittle et al. 1988; Pedlar et al. 1989), with about half of the NLR flux originating in two components, having velocities of  $680 \text{ km s}^{-1}$  and  $-480 \text{ km s}^{-1}$ , respectively.

In this paper we present NIR long-slit data of Mrk 78 with the aim of understanding and characterizing the mechanisms responsible for its emission spectrum. Mrk 78 is a Seyfert 2 with galactic extinction amounting to  $E(B - V) = 0.035$  mag (Schlegel et al. 1998). Its measured redshift ( $z = 0.0371$ ) (Michel & Huchra 1988) gives a distance of 150 Mpc and a physical scale of 715 pc/arcsec ( $H_0 = 75 \text{ km s}^{-1}$  is used throughout this paper). *HST* WFPC and FOC images taken in optical broad-band filters and  $[\text{O III}]\lambda 5007$  emission (Capetti et al. 1994; Whittle & Wilson 2004) show a complex structure of ionized gas aligned with the radio axis at  $\text{PA} = 84^\circ$ , plus a dust lane running across the galaxy center at  $\text{PA} = 135^\circ$  (see Fig.1). No signs of broad emission line region (BLR) emission has been detected from spectropolarimetry (Tran 1995). In the soft X-ray images, taken by *HRI/ROSAT*, Mrk 78 appears extended and its spectrum can be fitted by a thermal plasma plus galactic extinction (Levenson et al. 2001).

Section 2 describes the observations, and Section 3 presents the main results, covering first the nuclear emission to continue with the extended emission spectra and the kinematics obtained from the line profiles and line displacements. Section 4 discusses the extinction towards Mrk 78, and makes an attempt at disentangling the various ionizing mechanisms at play in Mrk 78. Finally, Section 5 summarizes the main conclusions.

## 2. Observations and Data Reduction

NIR spectra in the range  $0.8\text{--}2.4 \mu\text{m}$  were obtained on the night of 2005 March 22 at the 4.2 m William Herschel Telescope (WHT) using LIRIS, a recently commissioned NIR camera/spectrometer (Manchado et al. 2004; Acosta-Pulido et al. 2003). LIRIS is equipped with a Rockwell Hawaii  $1024 \times 1024$  HgCdTe array detector. The spatial scale is 0.25 arcsec/pixel and

the slit width used during the observations was  $1''$ , allowing a spectral resolution of  $600 \text{ km s}^{-1}$  and  $650 \text{ km s}^{-1}$  in the *ZJ* and *HK* spectra, respectively. The slit was oriented along  $\text{PA} = 80^\circ$ , centred on the galaxy nucleus (see Fig. 1). Weather conditions were relatively good, although with sparse cirrus. The seeing during our observations varied between 1 and  $1''.2$ , measured from the FWHM of the comparison stars in our NIR spectra.

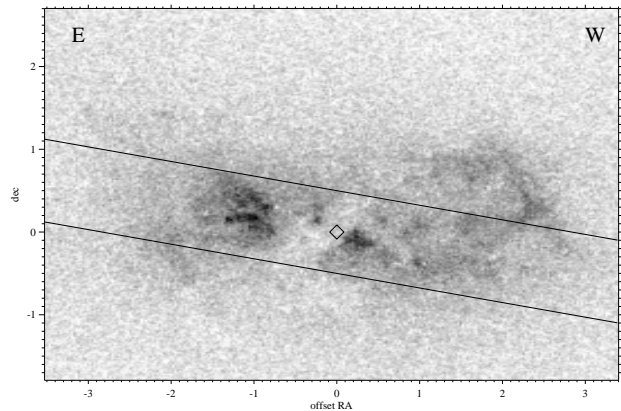


Fig. 1.— *HST*(WFPC)  $[\text{O III}]\lambda 5007$  image of Mrk 78, with the position of the LIRIS slit superimposed. The position of the brightest IR spot is marked with a diamond. The origin of the coordinate system is the same as reported Whittle & Wilson (2004)

Observations were performed following an ABBA telescope-nodding pattern, placing the source in two positions along the slit, separated by  $15''$ . Individual frames were taken with integration times of 300 s and total on-source integration times of 60 min in each of the *ZJ* and *HK* spectra. The wavelength calibration was provided by observations of argon and xenon lamps available in the calibration unit at the A&G box of the telescope. In order to obtain the telluric correction and the flux calibration, the nearby HD 61232 A0 V star was observed with the same configuration as the galaxy. The data were reduced following standard procedures for NIR spectroscopy, using IRAF<sup>1</sup>

<sup>1</sup>IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for the Research in Astronomy, Inc., under cooperative agreement with the National science Foundation. <http://iraf.noao.edu/>

and the LIRIS-QL dedicated software. Consecutive pairs of AB two-dimensional spectra were subtracted to remove the sky background. The resulting frames were then wavelength-calibrated and flat-fielded before registering and coadding all frames to provide the final spectrum. The final wavelength-calibrated galaxy spectra were divided by a composite spectrum to remove telluric contamination. This composite spectrum was generated from the observed spectra of A0 V star HD 61232, divided by a Vega model convolved with the actual spectral resolution as described by Vacca et al. (2003). Differences in the strength of telluric features likely due to mismatch of air masses and variation of atmospheric conditions between observations of the galaxy and the reference star are taken into account using Beer’s law. The IRAF task *telluric* was used in this step. The flux calibration was carried out by normalizing with the *JHK* magnitudes provided in the 2MASS survey catalogue (Cutri et al. 2003). The agreement in the continuum flux level in the overlap region for the *ZJ* and *HK* spectra is quite good in spectral shape and absolute value (about 15%).

### 3. Results

#### 3.1. Nuclear Emission

In order to study the nuclear emission we have extracted a spectrum covering 1.25 arcsec centred on the maximum of the galaxy profile. We have identified the maximum of the continuum as the position of the active nucleus and registered in the [O III] maps (see Fig. 1), as presented in Whittle & Wilson (2004). These authors have done the registration of the optical (with HST spatial resolution) and radio images using absolute ground-based astrometry (Clements 1981). They found a good alignment between the peak of the optical images and the position of the radio core. This fact gives confidence about the NIR peak should also coincide with the position of their nucleus. The resulting nuclear spectra in the *ZJ*, *H* and *K* ranges are plotted in Figs 2, 3, and 4, where the wavelength has been translated to the observer’s rest frame. The most obvious features in the nuclear spectra are [S III] $\lambda\lambda$ 0.907, 0.953, He I $\lambda$ 1.083, [Fe II] $\lambda\lambda$ 1.256, 1.643, Pa $\beta$ , Pa $\alpha$ , and the coronal line [Si VI] $\lambda$  1.962 (all wavelengths are given in

$\mu\text{m}$ ). The recombination line Br $\gamma$  is also present in the *K* band, although it appears very weak and is probably immersed in an absorption feature. For this reason its measured flux is subject to a large uncertainty. It is noteworthy to mention that in other Seyfert 2 galaxies, e.g., NGC 2273 and NGC 4569, this line is not found (Rhee & Larkin 2005).

Emission from the H<sub>2</sub> molecule is clearly detected, whose most prominent lines are the transitions H<sub>2</sub> 1-0 S(2) and H<sub>2</sub> 1-0 S(1). Both H<sub>2</sub> 2-1 S(1) and H<sub>2</sub> 1-0 S(0) emission lines are detected at  $\lesssim 2\sigma$  level.

Several other lower-intensity lines are detected in the *ZJ* spectra, namely [Ca I] $\lambda$  0.985, [S VIII] $\lambda$  0.991, He II $\lambda$  1.012, [S II] $\lambda$  1.032 (a blend of four [S II] transitions) and [P II] $\lambda$  1.188, which has particular relevance as a discriminator for different excitation mechanisms of the gas (Oliva et al. 2001).

Wherever possible all features were measured by fitting a Gaussian component using the program *twofitlines* (Acosta-Pulido 2000), developed in the IRAF environment, and the resulting values are reported in Table 1. The [Si VI] and H<sub>2</sub> 1-0 S(3) lines are strongly blended and two Gaussians were employed to separate the emission from these lines (the Starlink program DIPSO was used to perform the fits). The resulting fluxes and EWs are also reported in Table 1. The relative intensity between the H<sub>2</sub> 1-0 S(3) and H<sub>2</sub> 1-0 S(1) lines is 0.83, which is in good agreement with the theoretically predicted value of 1 for a wide range of conditions (Draine & Woods 1990), hence encouraging confidence concerning the deblending procedure. The [Si VI] line appears broader ( $\sim 70$  Å or 1100 km s<sup>-1</sup> after deconvolution) in comparison to other detected infrared lines ( $\sim 600$  km s<sup>-1</sup>). Rodríguez-Ardila et al. (2002) claimed a trend of increasing line widths with increasing ionization potential, perhaps indicating the existence of an emission region for the coronal lines closer to the nucleus than the classical NLR.

##### 3.1.1. Absorption-Line Features: The Stellar Population

Several absorption features are readily seen in the *H* band nuclear spectrum of Mrk 78 (see Fig. 3). In particular we observed the following ones: Mg I 1.50, CO 1.58, Si I 1.59, CO 1.62, CO 1.64

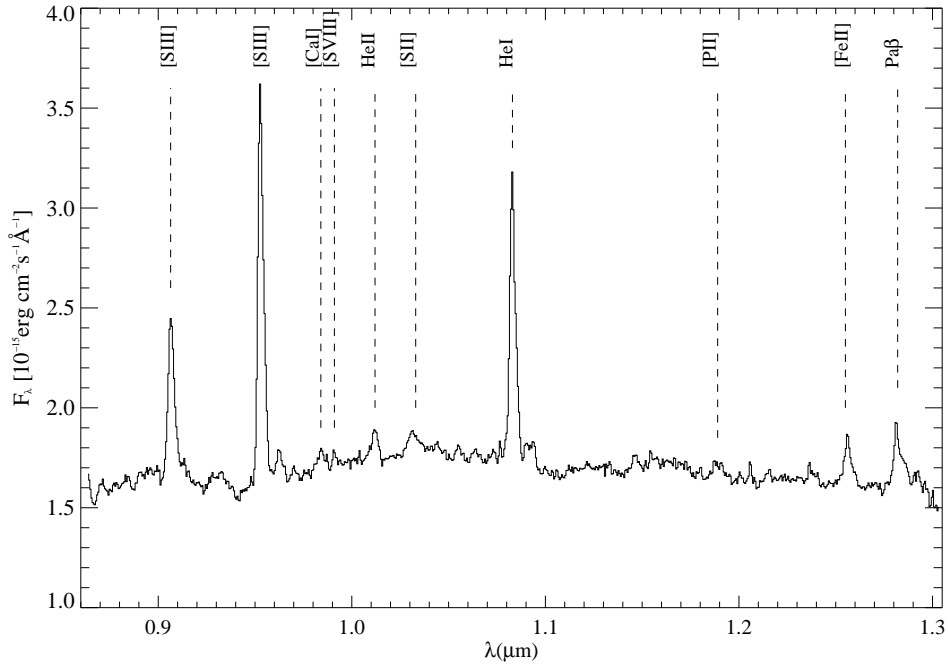


Fig. 2.— Flux-calibrated spectrum corresponding to the nuclear region of Mrk 78 within an aperture of  $1.25''$ , taken in the  $ZJ$  range. Note the simultaneous detections of high and low ionization lines, characteristic of AGN-like spectra.

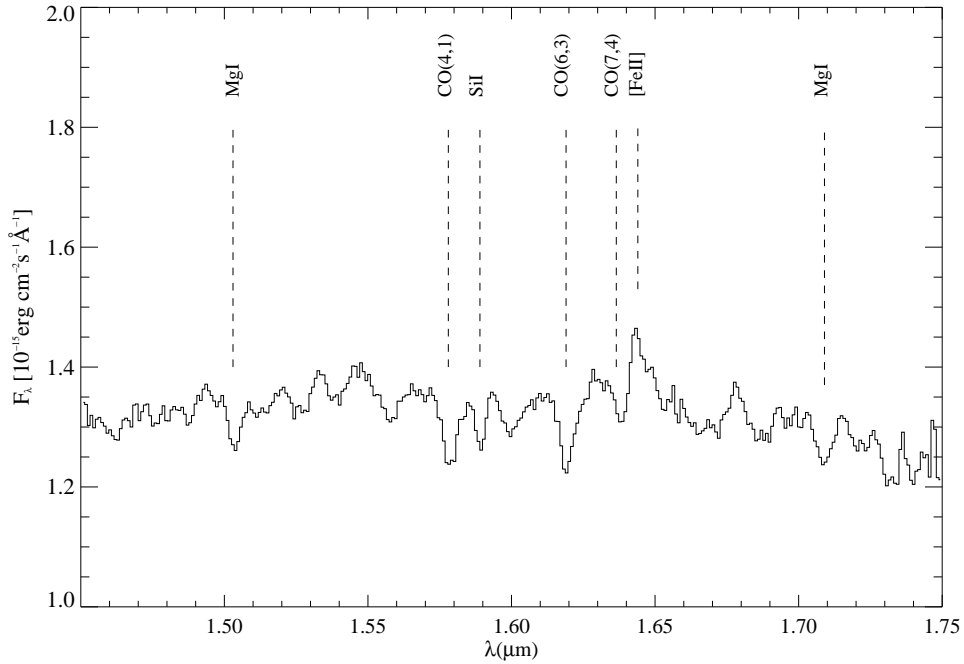


Fig. 3.— Same as Fig. 2 but in the  $H$  band. Note the conspicuous absorption features. This indicates a strong stellar contribution.

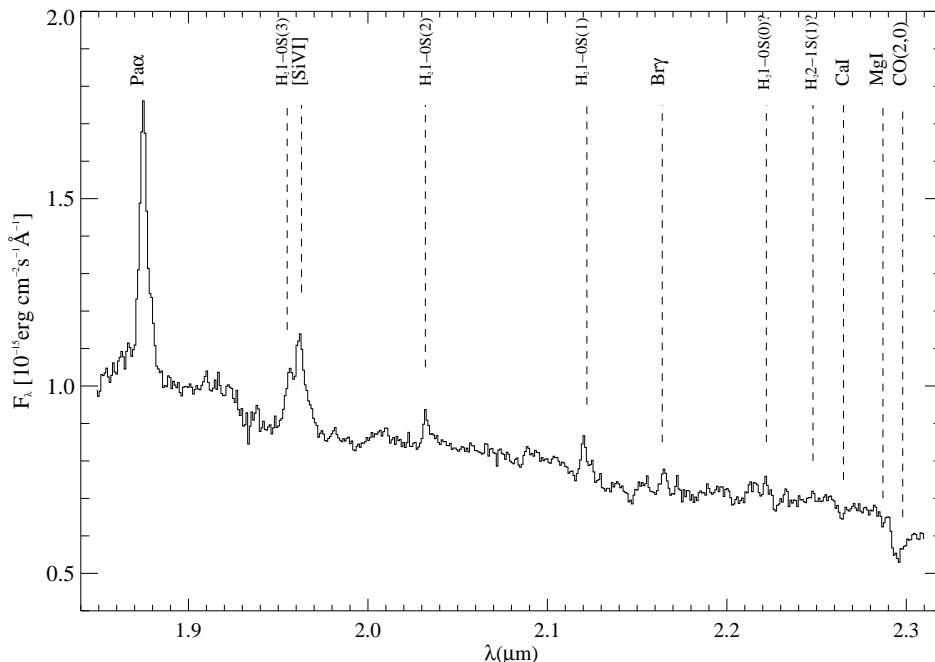


Fig. 4.— Same as Fig. 2 but in the  $K$  band. The most prominent line in this range is  $\text{Pa}\alpha$ , the high ionization line  $[\text{Si VI}]$  also appears very intense and several  $\text{H}_2$  emission lines are clearly detected.

and  $\text{Mg I } 1.71$  (all wavelengths are given in  $\mu\text{m}$ ). These features are named according to their main contributor, although, depending on the stellar spectral type, other species may become dominant. For example, for very cool stars,  $\text{OH}$  dominates the  $\text{Si I}$  feature (Origlia et al. 1993; Dallier et al. 1996). In the  $K$  band, we have also detected  $\text{Ca I } 2.26$ ,  $\text{Mg I } 2.28$  and the  $^{12}\text{CO}(2,0)$  band head, at  $2.29 \mu\text{m}$ . Unfortunately, the entire band is not included in our observations as part of it lies outside our spectral range due to the galaxy redshift.

The ratio of the equivalent width of the  $1.62 \mu\text{m}$   $\text{CO}(6,3)$  feature to that of the  $1.59 \mu\text{m}$   $\text{Si I}$  one is a good temperature indicator for late-type stars (Origlia et al. 1993; Förster Schreiber 2000; Ivanov et al. 2004), since the  $\text{CO}(6,3)$  feature grows rapidly from early K to late M stars, while the  $\text{Si I}$  one is only weakly dependent on stellar temperature. Moreover, dilution and reddening effects are cancelled out, due to the closeness of the features in wavelength.

In order to identify the spectral types that produce the absorption features seen in the  $HK$  range

of Mrk 78, we compare our spectra with digitally available stellar templates from Dallier et al. (1996), observed in the  $H$  band with a medium resolution. The equivalent width of the intrinsic stellar features have been computed after convolution of the templates, in order to match the resolution of our galaxy spectra. As a result of this comparison, for Mrk 78, the equivalent-width ratio of the  $\text{CO } 1.62$  feature to  $\text{Si I } 1.59$  corresponds to spectral types in the range K5 III to M3 III (see Table 2). This is consistent with results obtained by Oliva et al. (1995) for a range of galaxy types and with those of Thatte et al. (1997) for NGC 1068. An age of several hundred Myr is estimated for the stellar system, based on the fact that intermediate to low mass giants dominate the integrated IR luminosity (Renzini & Buzzoni 1986).

In Seyfert galactic nuclei, these late-type stellar features are substantially diluted by non-stellar nuclear emission. Assuming a single stellar population, the dilution fraction ( $D = 1 - \text{EW}_{\text{obs}}/\text{EW}_{\text{int}}$ ) can be computed from the ratio of measured to intrinsic EWs of any absorption feature (Oliva et al. 1995). Thus in the  $H$  band, using the  $\text{CO } 1.62$  feature, a starlight dilution

Table 1: Observed nuclear emission lines fluxes and EWs. The H<sub>2</sub>1-0S(0) and H<sub>2</sub>2-1S(1) fluxes reported here correspond to an upper limit of 2 $\sigma$ .

Line Nucleus	$\lambda$ ( $\mu\text{m}$ )	Flux ( $10^{-14}\text{erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ )	EW ( $\text{\AA}$ )
[SIII]	0.907	$3.54 \pm 0.21$	-21.5
[SIII]	0.953	$6.87 \pm 0.21$	-42.5
[CaI]	0.985	$0.39 \pm 0.06$	-3.03
[SVIII]	0.991	$0.17 \pm 0.03$	-1.62
HeII	1.012	$0.59 \pm 0.05$	-3.26
[SII]	1.032	$0.71 \pm 0.12$	-4.05
HeI	1.083	$5.40 \pm 0.14$	-31.3
[PII]	1.189	$0.53 \pm 0.09$	-2.38
[FeII]	1.256	$0.96 \pm 0.13$	-5.93
Pa $\beta$	1.282	$1.75 \pm 0.25$	-10.9
[FeII]	1.643	$0.85 \pm 0.23$	-6.25
Pa $\alpha$	1.875	$4.33 \pm 0.18$	-40.5
H <sub>2</sub> 1-0S(3)	1.955	$0.43 \pm 0.11$	-8.34
[SiVI]	1.962	$1.97 \pm 0.17$	-17.6
H <sub>2</sub> 1-0S(2)	2.032	$0.30 \pm 0.08$	-3.56
H <sub>2</sub> 1-0S(1)	2.121	$0.52 \pm 0.08$	-6.88
Br $\gamma$	2.165	$0.25 \pm 0.02$	-4.13
H <sub>2</sub> 1-0S(0)	2.222	:0.20	...
H <sub>2</sub> 2-1S(1)	2.248	:0.20	...

in the range 30–37% is obtained for the nuclear spectrum. For the  $K$  band CO(2,0) 2.29 we use, as intrinsic EWs for giant stars, those computed from the digitally available spectra from Wallace & Hinkle (1997), resulting in a dilution factor of 43-47% in this band (see Table 2). The stellar contribution in the  $J$  band was estimated from the colors of K–M giants. The remaining non-stellar spectrum resembles a power law ( $F_\nu \propto \nu^{-1.5}$ ). The index of this power law is relatively close to the average value ( $F_\nu \propto \nu^{-1.35}$ ) claimed for the NIR pure AGN emission (Neugebauer et al. 1979), which is steeper than in the optical range.

Another common way of determining the age of the stellar population in the NIR is by means of the strength of the CO absorption feature starting at 2.29  $\mu\text{m}$ . There are several working definitions of the CO index. We have used that given by Ivanov et al. (2000), which is more appropriate to the CO band measured in Mrk 78, where the spectrum ends beyond 2.31  $\mu\text{m}$ . Indeed, in Mrk 78, be-

cause of its redshift, the CO band feature is close to the edge of the atmospheric window; hence, measuring the continuum level on both sides of the feature is subject to large uncertainties. The Ivanov CO index is narrower than that of Doyon et al. (1994) and has the additional advantages of being insensitive to extinction, and to possible uncertainties in the continuum shape of the infrared spectra. We measure it as follows:

$$\text{CO} = -2.5 \log(\langle F_{2.295} \rangle / \langle F_{2.282} \rangle),$$

where  $\langle F_{2.282} \rangle$  and  $\langle F_{2.295} \rangle$  are the averaged flux within a bandwidth of 0.01  $\mu\text{m}$ , centred on the blue continuum and at the band head respectively. The resultant CO index is  $0.149 \pm 0.002$ , which is among the lowest values obtained for Seyfert 2 galaxies by Ivanov et al. (2000), as expected because these authors use a larger spatial scale. Our value is also lower than the average one corresponding to the sample of pure starburst galaxies as reported by the same authors. Knowing the dilution factor from the non-stellar component in the  $K$  band, which is approximately 45%, we can estimate the CO index after removing the non-stellar contribution, being its value  $0.289 \pm 0.007$ . In order to estimate an age from this CO index we need to transform its value into an age-calibrated one. First we convert our narrow spectral index into the broader, most usual one, using an expression from Ivanov et al. (2000):

$$\text{CO}(\text{Ivanov}) = (0.97 \pm 0.03) \cdot \text{CO}(\text{Doyon}) + (0.002 \pm 0.006)$$

We then obtain a photometric index using a linear relationship from Doyon et al. (1994):

$$\text{CO}_{\text{spec}} = 1.46 \cdot \text{CO}_{\text{phot}} - 0.02,$$

which gives a CO<sub>phot</sub> of  $0.216 \pm 0.023$ . Looking at Fig. 1 in Origlia & Oliva (2000), it is ambiguous as to which isochrone is most applicable to determine the age of the stellar population. It is well known that the CO band strength is sensitive to surface gravity and depends both on metallicity and effective temperature. For solar metallicity, the value of the index points to  $\sim 30$  Myr using Geneva tracks (Schaller et al. 1992), or to two different values, namely  $\sim 25$  and  $\sim 80$  Myr, if Padua tracks (Bertelli et al. 1994) are chosen. These ambiguities have led to the use of the CO index as an

age indicator being questioned. Origlia & Oliva (2000) claim that an inadequate treatment of the AGB phase produces CO features that are too weak, so that the results are fairly dependent on the evolutionary tracks one adopts. Nevertheless, if late-type giants were the dominant population in the nucleus of Mrk 78,  $\sim 100$  Myr would be a lower limit to the age of the stellar population, and the  $\sim 80$  Myr point would then be the only one possible for this case. Summarizing, we conclude that stellar features in the  $H$  and  $K$  bands are dominated by intermediate to low mass giants, with an estimated aged of approximately 100 Myr.

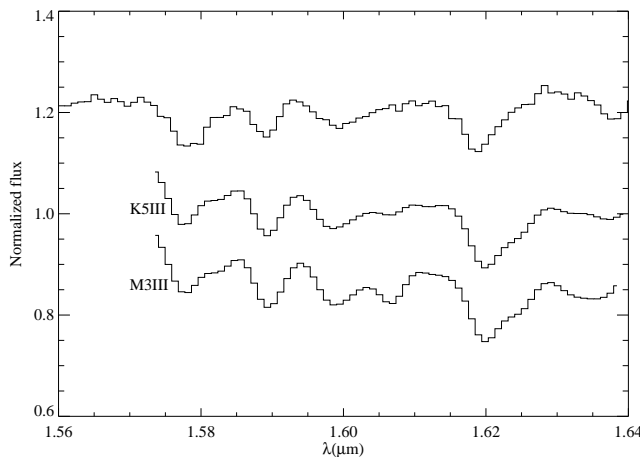


Fig. 5.—  $H$  band spectra of Mrk 78 (top) and two giant stars (K5 III and M3 III types). The spectra of the stars have been convolved and rebinned in order to obtain the same resolution as that of the galaxy spectrum. All spectra are normalized and shifted vertically for clarity.

### 3.2. Extended Narrow Line Region

Extended emission on both sides of the nucleus is observed, along the slit, in several spectral lines; namely, in  $[\text{Fe II}]\lambda\lambda$  1.256,1.643,  $[\text{S III}]\lambda\lambda$  0.907,0.953,  $\text{He I}\lambda$  1.083,  $\text{Pa}\alpha$ ,  $\text{Pa}\beta$  and  $[\text{Si VI}]\lambda$  1.962. The emission in weaker lines such as  $\text{Br}\gamma$  plus in several  $\text{H}_2$  molecular lines also appears extended although it becomes difficult to measure, as they are at about one  $\sigma$  level. The spectral features were measured by means of Gaussian fits using the in-house software utility *twofitlines* (Acosta-Pulido 2000). The spectra were extracted after coadding three columns along the spatial direction, equivalent to  $0''.75$ . However, in a region

around  $1''.5$  east of the nucleus several lines are split into two kinematic components (discussed in Section 3.3). In those cases the line fluxes are obtained by simple integration over the line profile.

Several line flux profiles are shown in Fig. 6, where the  $\text{Pa}\alpha$  profile has been chosen as a baseline against which to compare the other line profiles. We note that the flux distribution of  $\text{Pa}\alpha$  is asymmetric around the nucleus. It shows first a slow decline within  $1''.5$  east of the nucleus and then falls steeply beyond  $2''$ . Instead, on the opposite side of the nucleus the profile falls quickly  $1''$  west of the nucleus, further showing a shoulder at  $\sim 3''$ . The  $\text{Pa}\alpha$  emission profile can be compared with the high spatial resolution Mrk 78  $[\text{O III}]$  and radio images from Whittle & Wilson (2004). The radio image shows two lobes on both sides of the central nucleus, which is actually the brightest radio source. However, in  $[\text{O III}]$  radiation there are two cones of emission east and west of the center (Whittle & Wilson 2004), which is consistent with the existence of a nuclear obscuring structure. The large size of the  $[\text{O III}]$  obscured region suggests that obscuring material is required on a much larger scale in addition to the few parsec size torus (Pier & Krolik 1992) obscuring the active nucleus (Capetti et al. 1994). A transverse  $[\text{O III}]$  profile reveals that the emission is brighter  $1''.5$  to the east, decreasing towards the west after  $2''$ , just where the  $\text{Pa}\alpha$  shows a shoulder.

The high-ionization line ratio  $[\text{Si VI}]/\text{Pa}\alpha$  shows its maximum at the position of the nucleus. It also shows an enhancement  $2''.5$  east of the nucleus, while it stays low ( $\sim 0.1$ ) in the western lobe. This is a clear indication that the ionization is higher in the nucleus and also in the east lobe, compared to the west side.

In contrast, the  $[\text{S III}]/\text{Pa}\alpha$  line ratio shows a minimum at the nucleus and then increases to a nearly constant value in the lobes. Both these facts are indicative of a decrease in the ionization level outside the nucleus, as discussed below in Section 4.3.

The  $[\text{Fe II}]/\text{Pa}\alpha$  line ratio has an interesting behavior, showing a minimum at the position of the nucleus, while a high value, exceeding by a factor  $\sim 2$  the value in the eastern lobe, appears in the western one.

The  $\text{Pa}\beta/\text{Pa}\alpha$  ratio is an indicative of extinc-

Table 2: Absorption line feature Equivalent Widths in the H and K bands for Mrk 78 and for three giant stars classes. (\*M0III star)

Line	EW(Å)				Range( $\mu\text{m}$ )
	Mrk 78	K5III	M1III	M3III	
SiI $\lambda$ 1.589	2.3	2.8	2.9	2.9	1.585-1.592
CO(6,3) $\lambda$ 1.619	5.1	7.8	7.3	8.1	1.614-1.627
CO(2,0) $\lambda$ 2.290	8.1	14.1	15.2*	15.3	2.291-2.303

tion: there are some indications that the gas in the east and west lobes does not suffer so much extinction as in the nucleus, as concluded by Whittle & Wilson (2004).

The He I $\lambda$ 1.083/Pa $\alpha$  ratio shows a shallow peak coincident with the nucleus of the galaxy, indicating higher ionization than in the outer nebular regions.

Finally, the line ratios including H<sub>2</sub> indicate that the molecular emission is compact and concentrated towards the nucleus, although we cannot exclude the possibility that the molecular emission may extend in a direction perpendicular to the ionization cone as mentioned by Reunanen et al. (2003).

In summary, the scenario that we may envisage through these ratios consists of a prominent highly ionized nucleus, which is obscured by dust; an eastern lobe where the ionization parameter is also very high according to the [Si VI] emission (a line with a very high ionization potential); and a western lobe where the [Fe II] emission is mostly due to the higher radio-jet interaction in the west. Both lobes are less affected by extinction than the nucleus, as can be seen from the behavior of the Pa $\beta$ /Pa $\alpha$  ratio in Figure 6. This coincides with the existence of a dust band crossing the galaxy center, as can be seen in Figure 1.

### 3.2.1. Eastern and Western Emission

By looking at the variation of the line widths along the slit, we noted that there are two regions where the FWHM increases noticeably (see the discussion in Section 3.3). These positions coincide with the shoulders seen in the Pa $\alpha$  flux profile. For this reason we decided to study these zones separately. We extracted two spectra in the *ZJ* and *HK* ranges, one centred on 1''5 to the east, and the other 2'' to the west, covering 1.5

arcsec (see Figs 7, 8, and 9).

In the east lobe, the most prominent lines (He I $\lambda$ 1.083, [Fe II] $\lambda$ 1.257, Pa $\beta$  and Pa $\alpha$ ) appeared double-peaked, as can be seen in the insets of Figures 7 and 9. The two kinematic components correspond to a blue one, which is present overall along the slit, plus a weak red component, which is only detected close to this lobe. In the west zone, the FWHM appears slightly larger than the mean value, although it is not large enough to detect more than one kinematic component.

We report integrated fluxes for the red and blue components of the eastern and western regions in Table 3. The fluxes were measured by Gaussian fitting as described in Section 3.2. In the case of the east region we employed two components, the velocity difference between them being  $\sim 600 \text{ km s}^{-1}$ , whereas in the west region a single component was used.

The relative intensity of [Fe II] emission appears much brighter in the west; the values at the nucleus and at the east are similar. [Si VI] shows the largest value at the nucleus, and the lowest in the west lobe; intermediate and similar values are measured in the two components at the east lobe. Differences between the blue and red spectra on the east side are clearly seen in the [S III] and Pa $\beta$  fluxes relative to Pa $\alpha$  (see Table 3), showing a lower value for the blue component.

The depth of the stellar features appears very different in the east and west lobes (see Figs 8 and 9), being much larger in the east one. Quantitatively, in the east the dilution factor is around 20%, and in the west this factor is larger than 60%, measured from the CO(2,0) band head. Similar values are determined from the stellar absorption features in the *H* band. As expected for regions outside the nucleus, in the east lobe the stellar contribution dominates the continuum emission.



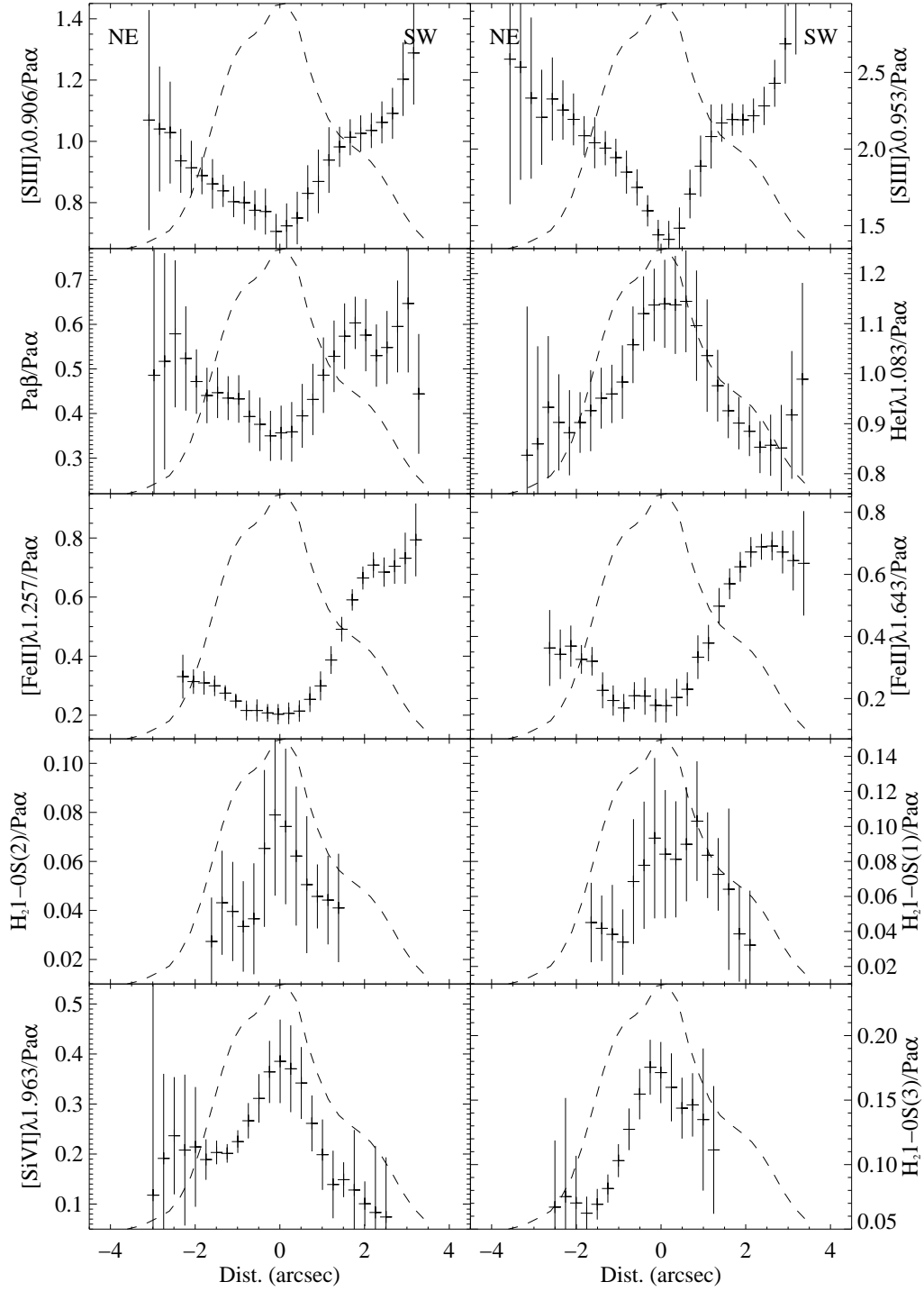


Fig. 6.— The most prominent emission line flux profiles vs distance from the nucleus, divided by the Pa $\alpha$  contribution. The dashed line represents the flux distribution of the Pa $\alpha$  line on a logarithmic scale.

In contrast, in the western lobe there could be an intense non-stellar continuum diluting the stellar counterpart, which could be related to the blue extended continuum claimed by Whittle & Wilson (2004), although its origin is still unclear. Otherwise, there could be an enhancement of old stellar population, that would contribute less to absorption features.

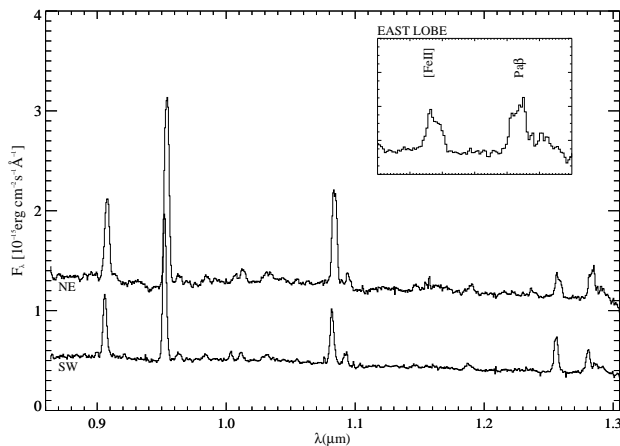


Fig. 7.— Flux-calibrated spectrum corresponding to  $1''.5$  to the east (top spectrum) and  $2''$  to the west (bottom spectrum) within an aperture of 1.5 arcsec, in the  $ZJ$  range. The inset shows an amplification of  $[\text{Fe II}]\lambda 1.257$  and  $\text{Pa}\beta$  double-peaked profiles in the east lobe.

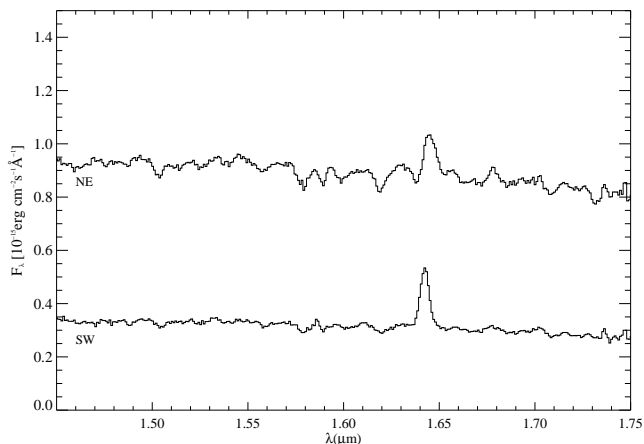


Fig. 8.— Same as Fig. 7 but in the  $H$  band. Note the difference in the depth of stellar features between the east and west lobes.

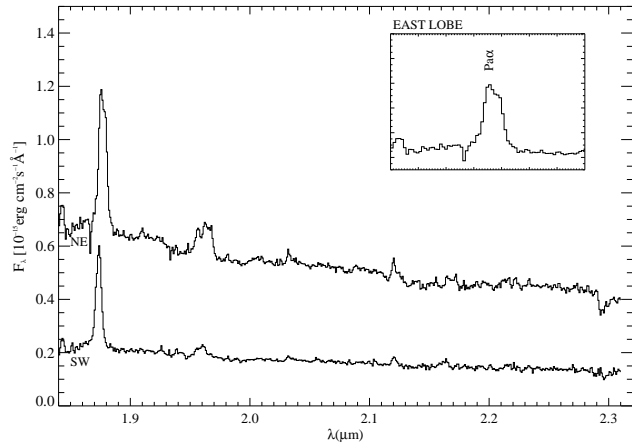


Fig. 9.— Same as Fig. 7 but in the  $K$  band. The inset shows an amplification of  $\text{Pa}\alpha$  double-peaked profile in the east lobe.

### 3.3. Kinematics of the Ionized Gas

A visual inspection of the two-dimensional spectrum reveals that the most intense emission lines describe what is most readily explained as a rotation curve, redshifted towards the east of the galaxy and blueshifted towards the west. Moreover, all lines appear to be resolved with an average line width of  $500 \text{ km s}^{-1}$ .

In order to analyze the velocity field we have fitted Gaussians to the line profiles, as described in the previous section. We note that around  $1''.5$  in the east and near  $2''$  in the west the measured line widths increase noticeably. The velocity field appears to be clearly perturbed in those regions. Furthermore, the presence of double-peaked profiles becomes evident in some of the lines around  $1''.5$  to the east, e.g.,  $\text{He I}\lambda 1.083$ ,  $[\text{Fe II}]\lambda 1.257$ ,  $\text{Pa}\beta$  and  $\text{Pa}\alpha$  (see Figs 7 and 9). We have plotted in Fig. 10 the velocity and FWHM variation along the slit. This has been done for an emission line where we clearly distinguish two components, namely  $\text{Pa}\alpha$ , and for another line, the  $[\text{S III}]\lambda 0.953$ , for which a single, though broader, component can be fitted. In both cases, the overall behavior resembles that of a galaxy rotation curve with a half amplitude of  $\sim 300 \text{ km s}^{-1}$ .

The  $\text{Pa}\alpha$  line profile, in the eastern lobe, can be split into two kinematic components, a blueshifted one, roughly corresponding to the nominal rotation field, and a redshifted one, with a larger mean

TABLE 3

NUCLEAR, SW AND NE (RED AND BLUE COMPONENTS) FLUXES NORMALIZED TO  $\text{Pa}\alpha$  FOR THE MOST PROMINENT LINES, ALL OF THEM FITTED BY GAUSSIANS.

Line Nucleus	$\lambda(\mu\text{m})$	Nuclear emission	SW emission	Blue NE emission	Red NE emission
[SIII]	0.907	$0.82 \pm 0.08$	$1.02 \pm 0.07$	$0.68 \pm 0.23$	$1.16 \pm 0.25$
[SIII]	0.953	$1.59 \pm 0.11$	$2.22 \pm 0.13$	$1.45 \pm 0.11$	$2.56 \pm 0.16$
HeII	1.012	$0.14 \pm 0.02$	$0.12 \pm 0.02$	$0.13 \pm 0.02$	$0.13 \pm 0.02$
HeI	1.083	$1.25 \pm 0.08$	$0.89 \pm 0.06$	$1.16 \pm 0.07$	$0.96 \pm 0.07$
[FeII]	1.256	$0.22 \pm 0.04$	$0.61 \pm 0.05$	$0.29 \pm 0.04$	$0.22 \pm 0.05$
$\text{Pa}\beta$	1.282	$0.40 \pm 0.07$	$0.45 \pm 0.05$	$0.32 \pm 0.04$	$0.51 \pm 0.06$
[FeII]	1.643	$0.20 \pm 0.06$	$0.63 \pm 0.06$	$0.29 \pm 0.04$	$0.15 \pm 0.04$
$\text{Pa}\alpha$	1.875	1.00	1.00	1.00	1.00
[SiVI]	1.962	$0.45 \pm 0.06$	$0.09 \pm 0.04$	$0.24 \pm 0.02$	$0.26 \pm 0.03$

velocity of  $\sim 600 \text{ km s}^{-1}$ , which may correspond to gas accelerated by interaction with the radio jet, as proposed by Whittle & Wilson (2004).

As stated above, the FWHM also increases at  $2''$  towards the west (see Fig. 10), suggesting that the gas dynamics in this region are also affected by the interaction with the radio jet. However, the spectral resolution of our spectra does not allow us to distinguish the different kinematic components.

## 4. Discussion

### 4.1. Extinction towards the Nucleus

According to the unification scheme for Seyfert galaxies, the nucleus of Mrk 78 should be hidden from our view. This is apparently the case, as for instance Capetti et al. (1994) claim strong obscuration towards the nucleus of Mrk 78, based on different arguments. They found that the observed UV flux is at least three orders of magnitude smaller than the flux required to ionize the NLR. Based on this fact, applying the reddening curve from Cardelli et al. (1989) and the standard dust-to-gas ratio, they estimated a lower limit for the column density of  $N_{\text{H}} > 0.5 \times 10^{22} \text{ cm}^{-2}$ . They also concluded that the nuclear emission must be intrinsically anisotropic in order to explain the observed low infrared luminosity as compared to the nuclear luminosity required to account for the overall NLR luminosity. Besides, Whittle & Wilson (2004) showed color images in which the nuclear extinction is clearly seen across several hun-

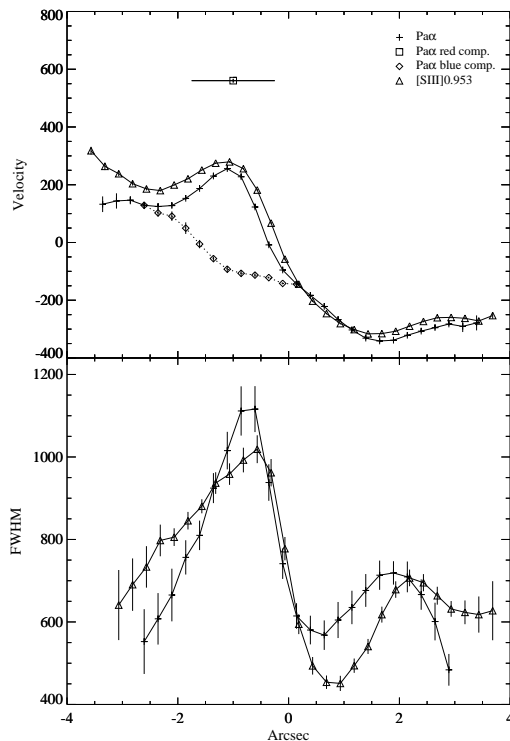


Fig. 10.— Variation of velocity and FWHM (both in  $\text{km s}^{-1}$ ) measured from the lines  $\text{Pa}\alpha$  (crosses) and [S III] $\lambda 0.953$  (triangles). The overall measurements (fitted by a single Gaussian) are represented by continuous lines. For the  $\text{Pa}\alpha$ , which can be split into two components, the dashed line (diamonds) represents the blue component whereas the square indicates an average value for the red one.

dred parsecs. Indeed, we have not detected any broad wings in the H recombination lines present in our spectra. Previously, Goodrich et al. (1994) reported the non-detection of a broad component for Pa $\beta$  in this galaxy, although their spectra have much lower signal to noise ratio than ours.

Moreover, the extinction towards the nucleus can be estimated from our spectra using several reddening indicators, such as the [Fe II] $\lambda$ 1.257 and [Fe II] $\lambda$ 1.644 lines, or other line ratios between the observed Paschen and Brackett H recombination lines. From these line ratios we have determined the optical extinction,  $A_V$ , using Draine’s parameterization (Draine 1989)  $A_\lambda \propto \lambda^{-1.75}$ . The results are presented in Table 4. The [Fe II]1.257/1.644  $\mu\text{m}$  line ratio is a reliable indicator given that it is not dependent on the density or temperature of the line-emitting gas. We measured a value of 1.13 (see Table 4), which yields a moderate value for the extinction when compared to the theoretical value of 1.34 (Bautista & Pradhan 1998). The [Fe II]1.257/1.644 line ratio measured for Mrk 78 is very close to the mean value 0.98 found in a sample of Seyfert galaxies by Rodríguez-Ardila et al. (2004). These authors argued that either the gas emission [Fe II] lines are affected by the same large extinction for most Seyfert galaxies, or the theoretical value is overestimated, given the uncertainties in the determination of the transition coefficients.

Other available reddening indicators are the Pa $\beta$ /Pa $\alpha$  and the Pa $\alpha$ /Br $\gamma$  line ratios. However, these ratios depend on the density and temperature of the line-emitting gas. In particular, the Pa $\beta$ /Pa $\alpha$  ratio varies by  $\sim 8\%$  when the temperature changes from 5000 to 20000 K (Hummer & Storey 1987). We have adopted theoretical values corresponding to  $T_e = 10000$  K and  $N_e = 10^4 \text{ cm}^{-3}$ . In our case, the observed Pa $\alpha$ /Br $\gamma$  line ratio is larger than the theoretical value. This could be due to an underestimation of the Br $\gamma$  line flux, because of either the weakness of the line or an underlying absorption feature.

The values derived for the visual extinction agree very well with those estimated by other authors using narrow emission lines (Veilleux et al. 1997; Rodríguez-Ardila et al. 2004). It is worth mentioning that the extinction measured using these narrow lines provides only an indication of the material located between us and the NLR.

However, the nucleus itself and the BLR may be hidden by a larger amount of material. In fact, the non-detection of broad wings in recombination lines implies a lower limit of  $A_v > 10$  (Veilleux et al. 1997), if we assume the existence of a hidden BLR.

## 4.2. The Emission-Line Spectrum

The simultaneous observation of very high and low ionization lines imply that a wide variety of physical conditions must coexist in the nuclear region of Mrk 78. This is a characteristic feature of gas photoionized by a power-law radiation source extending from the UV through X-rays. In particular the detection of strong coronal lines such as [Si VI] $\lambda$ 1.962 (IP = 166.7 eV) and [S VIII] $\lambda$ 0.991 (IP = 280.9 eV) are indicative of the presence of extreme UV and X-ray photons (Prieto & Viegas 2000).

Marconi et al. (1994) concluded that the [Si VI] $\lambda$  1.962 emission line is associated uniquely with Seyfert 1 and 2 nuclei, and can only be produced by photoionization by a hard nuclear continuum. Furthermore, they indicate that this line must be produced in a dense gas with large column densities. Hot stars, present in HII regions are not capable of exciting the [Si VI] line, neither increasing the ionization parameter nor the ionizing star temperature. This coronal line is therefore an excellent tracer of Seyfert activity in galaxies with visually obscured nuclei. Indeed, Oliva & Moorwood (1990) found strong [Si VI] in NGC 1068 despite the strong obscuration present in this Seyfert galaxy. Coronal lines are forbidden transitions of highly ionized species, which are formed in extreme energetic environments. Reunanen et al. (2003) observed that coronal line emission appears to be extended along the ionization cone axis, implying an anisotropic nuclear radiation field. Furthermore, coronal lines are seen with similar strength and frequency in both Seyfert types (Prieto & Viegas 2000), thus their study provides a clean test of the Unification Model.

### 4.2.1. The Origin of the Intense [Fe II] Emission

It is well known that [Fe II] emission is weak in HII regions but strong in the shock-excited filaments of supernova remnants. In AGN, strong [Fe II] emission is also common, although there

TABLE 4

THEORETICAL AND MEASURED EMISSION LINE RATIOS AND  $A_V$  VALUES, CALCULATED USING DRAINE'S PARAMETRISATION.

Ratio	Theoretical	Measured	$A_V$
[FeII]1.26/1.64	1.34	$1.13 \pm 0.34$	1.97
Pa $\beta$ /Pa $\alpha$	0.49	$0.40 \pm 0.07$	1.85
Pa $\alpha$ /Br $\gamma$	12.2	$17.3 \pm 1.6$	...

is still some controversy about what is the dominant process responsible for this emission. Several processes may contribute to the production of the [Fe II] lines: 1) photoionization by soft X-ray–extreme UV radiation from the central source, producing large partially ionized regions in NLR clouds of high optical depth; 2) the interaction of radio jets with the surrounding medium, which induces shocks and produces partially ionized cooling tails; and 3) fast shocks associated with supernova remnants present in starburst regions. The [Fe II] $\lambda$ 1.257/Pa $\beta$  line ratio, or equivalently [Fe II] $\lambda$ 1.644/Pa $\alpha$ , has proved to be very useful for distinguishing between a stellar and non-stellar origin for the [Fe II] emission. These line ratios increase from HII regions (photoionization) to supernovae remnants (shock excitation), passing through starburst and active galaxies (Alonso-Herrero et al. 1997; Rodríguez-Ardila et al. 2004). Galaxies with [Fe II] $\lambda$ 1.644/Pa $\alpha$ <sup>2</sup> lower than 0.11 are classified as starbursts generally, LINERS if this value is larger than 0.75, and Seyfert galaxies are contained in the range 0.15–0.75 (Larkin et al. 1998; Rodríguez-Ardila et al. 2004). In the case of Mrk 78, the [Fe II] $\lambda$ 1.644/Pa $\alpha$  line ratio is seen to increase outside the nucleus and shows larger values in the west lobe (see Section 4.3). We found [Fe II] $\lambda$ 1.644/Pa $\alpha$  = 0.2 for the nuclear emission and similar values in the east lobe that are well within the range of Seyfert galaxies. Those values can be explained as due to photoionization by hard UV nuclear radiation (see Fig. 12). Starburst activity is not sufficient to explain these values. In the west lobe a higher value, [Fe

II] $\lambda$ 1.644/Pa $\alpha$  = 0.63, was measured that is closer to the LINER locus, probably related to shock excitation, associated with a more efficient interaction with the radio jet. In order to explain the [Fe II] $\lambda$ 1.644/Pa $\alpha$  line ratio in the west lobe a composite model including shock excitation plus photoionization by the nuclear radiation is required.

On the other hand, we have detected [P II] $\lambda$  1.188  $\mu$ m, which is an important emission line for discriminating between the different excitation mechanisms acting in the NLR. In particular, this line is very useful when compared with the [Fe II] $\lambda$  1.257 line (Oliva et al. 2001). Both lines are produced in partially ionized regions having similar critical densities and excitation temperature. In contrast, iron is a well known refractory species and is strongly depleted in dust grains, whereas phosphorus is a non-refractory species. Photoionization alone is unable to destroy the tough iron-based grains, while these are easily sputtered by shocks. The [Fe II]/[P II] ratio is high ( $\gtrsim 20$ ) in fast shock-excited regions and low ( $\lesssim 2$ ) in normal photoionized regions (Oliva et al. 2001). For Mrk 78 this line ratio is 1.82 in the nuclear region, indicating that photoionization by a soft X-ray continuum is the most likely mechanism responsible for the observed nuclear spectrum.

#### *The Extended [Fe II] Emission and Its Relationship to Radio Emission*

As pointed out by Rodríguez-Ardila et al. (2004), the [Fe II] $\lambda$ 1.644/Pa $\alpha$  line ratio is a good discriminator to discern between a stellar or non-stellar origin for the [Fe II] emission, although it is not helpful in distinguishing between processes in the latter case. In addition, shocks may efficiently destroy dust grains and release iron into the gas

<sup>2</sup>We transform the [Fe II] $\lambda$ 1.257/Pa $\beta$  line ratio to [Fe II] $\lambda$ 1.644/Pa $\alpha$  using the theoretical relations for both [Fe II] and H Paschen lines. The following equation was used [Fe II] $\lambda$ 1.644/Pa $\alpha$  =  $0.37 \times$  [Fe II] $\lambda$ 1.257/Pa $\beta$ .

phase, leading to an enhancement of the [Fe II] emission. An excellent way to differentiate between the different processes is the comparison of the [Fe II] emission and radio emission morphologies, despite the difficulty in obtaining [Fe II] images. Blietz et al. (1994) showed that the morphology of the [Fe II] emission correlates with that of the radio jet in NGC 1068. The most intense [Fe II] emission appears slightly offset upstream of the radio bow shock (see Fig. 2 in Blietz et al. (1994)). Mrk 78 may be a similar case in which the morphology of the [O III]-emitting gas seems to reflect different processes in the west and east lobes. The east lobe can be explained as a relatively homogeneous gas structure illuminated by the nuclear radiation source, which is penetrated by the radio emission. In contrast, the west lobe resembles a knotty gas distribution where the interaction with the radio jet has dispersed cloud fragments and swept out gas, producing compression of the gas (Whittle & Wilson 2004).

#### 4.2.2. The Origin of the H<sub>2</sub> Emission

Several molecular hydrogen emission lines are present in the *K* band spectrum of Mrk 78. These lines are clearly detected in the nucleus and in the east lobe (see Figs 4 and 9), although the emission is mostly concentrated in the nuclear region. Reunanen et al. (2003) reported that H<sub>2</sub> emission is spatially resolved preferentially in directions perpendicular to the ionization cone, which is in contrast with the results reported by Quillen et al. (1999), where H<sub>2</sub> emission coincides with [O III] and H $\alpha$  emission.

There are three possible H<sub>2</sub> excitation mechanisms in galaxies: i) UV pumping (fluorescence), ii) thermal excitation due to the presence of shocks, and iii) hard X-ray photons, which can penetrate deep into molecular clouds. These three mechanisms produce different spectral features, and the relative emission line intensities can be used to identify the dominant mechanism. In particular the H<sub>2</sub> 2–1 S(1)/1–0 S(1) line ratio is lower for thermal excitation (0.1–0.2) than for UV fluorescence ( $\sim 0.55$ ), as proposed by Mouri (1994). The value obtained for the nuclear region of Mrk 78 is  $\lesssim 0.38$ , which is larger than the predictions for pure thermal excitation, but smaller than those for non-thermal UV excitation. However, in the case of dense gas ( $N_e \geq 10^4$

cm<sup>-3</sup>), collisional de-excitation of the H<sub>2</sub> molecule modifies the spectrum, approaching the thermal spectrum. Excitation by hard X-ray are ruled out by other authors based on considerations of energetics (Rodríguez-Ardila et al. 2004) and on the detection of the transition H<sub>2</sub> 2–1 S(3) in several Seyfert galaxies (Davies et al. 2005), which would otherwise be suppressed in the case of X-ray irradiated gas (Davies et al. 2005).

Another way to discriminate between the thermal and fluorescent excitations is through the rotational and vibrational temperatures. In the case of thermal excitation both temperatures should be similar, whereas in the case of fluorescent excitation a high vibrational temperature will be in contrast with a lower rotational temperature. We have determined both temperatures using the expressions given by Reunanen et al. (2002) using the H<sub>2</sub> line ratios 2–1 S(1)/1–0 S(1) and 1–0S(0)/1–0S(2). The values obtained for this galaxy are  $T_{\text{vib}} \lesssim 4405$  K and  $T_{\text{rot}} \gtrsim 1557$  K, which are in good agreement with those derived by Rodríguez-Ardila et al. (2004) for a number of Seyfert 2 galaxies, such as Mrk 279 and NGC 5728. Hence, the most likely mechanism for the excitation of H<sub>2</sub> in Mrk 78 is UV fluorescent in a dense gas. Note, however, that, given the large uncertainties in the line flux measurements, thermal excitation cannot be ruled out.

### 4.3. Comparison with Photoionization Models

We have used the photoionization code CLOUDY (version C05.07.06), in order to reproduce the line ratios obtained from our spectra (for a detailed description see Ferland (2003)). We computed a grid of models based on photoionization by a power-law continuum and physical conditions in the gas typical of NLR. For the ionizing continuum we used a power-law shape of the form  $f_\nu \sim \nu^\alpha$ , where  $\alpha = -2$  is the spectral index in the range above 10  $\mu\text{m}$ . At energies below 10  $\mu\text{m}$  the spectral index is  $\alpha = 5/2$ . We assume a plane-parallel geometry, metallicity equal 0.3 solar, and grains with properties similar to those of the Orion Nebula, which corresponds to the best-fitting models according to Alonso-Herrero et al. (1997). Three different values of hydrogen density were explored:  $n_{\text{H}} = 10^4$ ,  $10^5$ , and  $10^6$  cm<sup>-3</sup>. An input to the code is the ionization parameter  $U$ , defined by

$$U = Q_{\text{H}}/(4\pi d^2 n_{\text{H}} c).$$

Line ratio diagrams are shown in Figs 11 and 12 for the following combination of lines: He II  $\lambda$ 1.012/Pa $\alpha$  versus [S III]  $\lambda$ 0.953/Pa $\alpha$  and [Si VI]  $\lambda$ 1.963/Pa $\alpha$  versus [Fe II]  $\lambda$ 1.644/Pa $\alpha$ . Dashed lines represent the computed line ratios for the three hydrogen densities employed, beginning with an ionization parameter of  $\log U = 0$  and decreasing it with a step of 0.5, towards the bottom of these plots.

Values of these line ratios from Table 3, corresponding to the nucleus, the west and the east lobes (red and blue components for the latter), are overplotted for comparison with our simulations made with CLOUDY. It can be seen that data from our spectra are compatible with photoionization models for all regions considered within values of  $\log U$  in the range  $-1$  to  $-2$ , except for the [Fe II]/Pa $\alpha$  line ratio. By looking at the diagram in Fig. 11, the best fit for the nucleus and the east lobe–blue component is obtained when  $\log U \sim -1.5$ . However, for the west lobe and east lobe–red component, the best fit is obtained when  $\log U \sim -1.8$ . In all cases the H density is close to  $n_{\text{H}} = 10^5 \text{ cm}^{-3}$ , which approaches the critical density for the [S III] line. From Fig. 12, it is easy to see that the [Si VI]/Pa $\alpha$  line ratio is very sensitive to the value of the ionization parameter, becoming saturated at values  $\log U \sim -0.5$ . At higher values of the ionization parameter, the [Si VII]  $\lambda$ 2.480 transition will become more important. The nuclear emission can thus be explained with values  $\log U \sim -0.5$ , whereas in the east lobe this value decreases to  $\log U \sim -1.3$ , and in the west lobe to  $\log U \sim -1.6$ . The differences between the best-fitting values of  $U$  from the different line ratios may be reconciled by lowering the spectral index of the power law, i.e., hardening the ionizing continuum, or using combination of clouds with different optical depths. In order to explain the [Fe II]/Pa $\alpha$  ratio, models may have to include effects due to interaction with the radio emission, such as increasing the iron abundance after grain sputtering.

We therefore conclude that the measured line ratios from the spectra of Mrk 78 are compatible with photoionization by an AGN-like continuum.

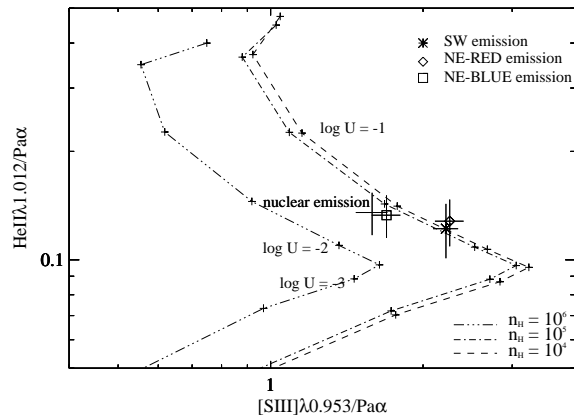


Fig. 11.— He II  $\lambda$ 1.012/Pa $\alpha$  versus [S III]  $\lambda$ 0.953/Pa $\alpha$  diagnostic diagram computed with the photoionization code CLOUDY. Models are calculated for a power-law continuum (index -2), different values of H density (different line types) and a sequence of ionization parameters. The marks along the U-sequence are separated by  $\log U=0.5$ . Our measurements are also overplotted: cross for the nucleus; asterisc for SW lobe; square for the blue component in the NE lobe; diamond for the red component in the NE lobe.

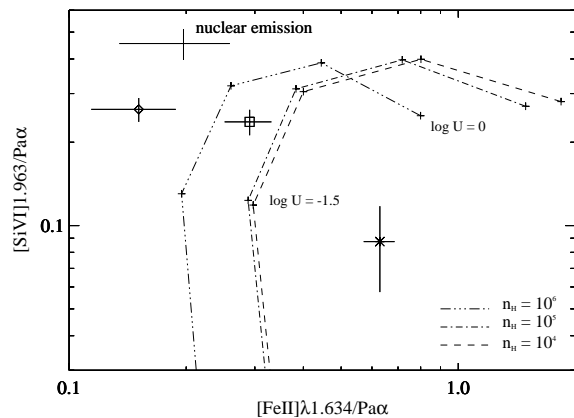


Fig. 12.— Same as Fig. 11 but with [Fe II]  $\lambda$ 1.644/Pa $\alpha$  versus [Si VI]  $\lambda$ 1.963/Pa $\alpha$ . The meaning of symbols is the same as in Fig. 11

## 5. Conclusions

We have presented and analyzed the NIR line spectrum of the nucleus and extended NLR of the Seyfert 2 galaxy Mrk 78. The following results were found:

- The nuclear spectrum and the extended NLR spectrum are produced by photoionization by a hard UV–X-ray continuum, as

indicated by the presence of the [Si VI] and [P II] lines. This fact is in good agreement with the presence of a hidden active nucleus in Mrk 78.

- The nuclear emission in the  $H$  band has numerous stellar absorption features. According to the relative equivalent widths, the stellar population is dominated by K–M giants in this wavelength range. The nuclear stellar emission is diluted by a non-stellar component by a factor  $\sim 34\%$  in the  $H$  band and  $\sim 45\%$  in the  $K$  band.
- An enhancement of the [Fe II] emission is observed outside the nucleus, in particular at  $\sim 2''$  to the west. This effect is interpreted in terms of the interaction with the radio emission.
- Several transitions of the  $H_2$  molecule are detected in the  $K$  band. The dominant excitation mechanism could not be determined unambiguously, although we favor UV fluorescence in a dense gas.

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The image presented in Fig. 1 is based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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