Deep Hα Observations of NGC 253: a Very Extended and Possibly Declining Rotation Curve?

J. Hlavacek-Larrondo1,2*, C. Carignan1,3, O. Daigle1,4, M.-M. de Denus–Baillargeon1, M. Marcelin4, B. Epinat4,5, O. Hernandez1

1Laboratoire d’Astrophysique Expérimentale, Département de physique, Université de Montréal, C.P. 6128, Succ. centre-ville, Montréal, Québec, Canada, H3C 3J7
2Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA
3Observatoire d’Astrophysique de l’Université de Ouagadougou, BP 7021, Ouagadougou 03, Burkina Faso
4Laboratoire d’Astrophysique de Marseille, Université de Provence, CNRS, 38 rue Frédéric Joliot-Curie, F-13388 Marseille Cedex 13, France
5Laboratoire d’Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 Avenue Edouard Belin, F-31400 Toulouse, France

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ABSTRACT
This study presents a deep Hα kinematical analysis of the Sculptor Group galaxy NGC253. The Fabry-Perot data were taken with the 36-cm Marseille Telescope in La Silla, Chile, using an EMCCD detector. Typical emission measures of ∼ 0.1 cm−6 pc are reached. The observations allow the detection of the Diffuse Ionized Gas component through [N ii] emission at very large radii of 11.5′, 12.8′ and 19.0′, on the receding side of the galaxy. No Hα emission is observed at radii larger than the neutral component (11.5′). The very extended rotation curve confirms previous results and shows signs of a significant decline, on the order of 30 per cent vmax. Using the rotation data, mass models are constructed with and without the outer [N ii] data points, and similar results are found. The declining part of the rotation curve is very well modeled, and seems to be truly declining.

Key words: galaxies: NGC 253 - galaxies: kinematics and dynamics - galaxies: ISM - instrumentation: interferometers - techniques: radial velocities.

1 INTRODUCTION
The Sculptor Group harbours an impressive amount of gas-rich late-type galaxies (de Vaucouleurs 1959), including NGC 7793, NGC253, NGC 300, NGC 247 and NGC 55. Several other small galaxies are known to be gravitational bound to the group (Cote et al. 1997). The galaxies are located at a distance estimated between 1.5 and 4 Mpc (Jerjen, Freeman & Binggeli 1998; Karachentsev et al. 2003). Its proximity, as well as the fact that its galaxies are isolated, makes it an ideal ground for studying the kinematical properties of disc galaxies. Moreover, the majority of its galaxies being late-type with no or almost no bulge, renders them excellent tools for studying the properties of dark matter haloes (Carignan & Freeman 1985).

The literature contains many studies of the Sculptor Group galaxies. Among them, a deep Hα study of NGC 7793 was performed by (1991). This study, based on deep optical Fabry-Perot (FP) data, confirmed that NGC 7793 has a truly declining rotation curve. Deep surveys of galaxies are essential to extract very extended rotation curves, and allow better constraints on the dark halo parameters. This study aims at studying the dynamical properties of another galaxy belonging to the Sculptor Group, NGC 253, also using deep Hα FP data.

NGC 253 is a late-type spiral starburst galaxy. The central regions show significant activity, and have therefore been thoroughly studied. H53α and H72α observations showed the presence of a counter-rotating central disc (Zhao et al. 2001). Furthermore, observations of the H2 emission line suggest the presence of gas being ejected to distances of 130 parsecs above the disc (Sugai, Davies & Ward 2003). Puche, Carignan & van Gorkom (1991) presented a kinematical study of the neutral gas component (H1) using 21-cm synthesis observations. A rotation curve extending to a maximum radius of 8.5 kpc (or 11.5′) was derived, and showed that even at the largest radius, the rotation curve continues to rise with a maximum velocity of 224 km s−1. A long-slit Hα study has also been done by Arnaboldi et al. (1993).

The Diffuse Ionized Gas (DIG) is an important component of the interstellar medium that can extend to large...
Table 1. Optical parameters of NGC 253

| Morphological type | SAB(s)c |
|-------------------|---------|
| R.A (2000)        | 00^h47'm33.s1^s |
| Dec. (2000)       | -25°17'18'' |
| Isophotal major diameter | 15.0 | |
| H0 radius         | 27.5'' |
| Exponential scale length | 17.5'' |
| Axis ratio        | 0.23 |
| Inclination       | 79.8° |
| Total apparent B magnitude | 8.05 |
| Total corrected apparent B magnitude | 7.09 |
| Adopted distance (Mpc) | 2.58 |
| Absolute B magnitude | -19.97 |
| Total blue luminosity (M_B = 5.43), L_B^⊙ | 14.4 x 10^9 |

1RC3
2Puche et al. (1991)
3Internal absorption A(α) = 0.91 (RC3).
4Galactic extinction A_K = 0.05 (RC3).
5Pence (1980)
6Puche & Carignan (1988)

2 FABRY-PEROT OBSERVATIONS AND DATA REDUCTION

2.1 Observations

The FP observations were obtained on the 36-cm Marseille Telescope at La Silla, Chile, from 2007 October 3 to 2007 October 15. A commercial camera Andor iXon, equipped with an EMCCD detector, was used (see Daigle et al. 2004). All the observations were made with the same filter, camera and FP etalon. Dark frames were taken at the beginning and end of each night. Furthermore, data were taken to calibrate the gain of the EMCCD. Flats with the etalon and Hα filter kept in place were also taken at twilight. The interference filter had a central wavelength of λ_c = 6561.0 Å, a FWHM of 30 Å, and a maximum transmission of ~ 80 per cent at a temperature of 10° Celsius, see Fig. 3. The FP interference order was p = 765 at Hα, with a Free Spectral Range (FSR) of 8.58 Å. The mean Finesse during the observations was ~16, with an etalon spectral resolution of ~ 0.53 Å (Δλ = FSR(Å)/Finesse). The data were scanned throughout the FSR over 40 channels of 0.21 Å per channel. Wavelength calibration was performed using a neon lamp (Ne) at 6598.95 Å. Several observations of the calibration cube were made during each night. For each observation of the calibration data, the etalon was scanned during one complete cycle (40 channels), with an exposure of 1 second per channel. The EMCCD has 512 x 512 pixels and a resolution of 2.77''/pixel. Each field covers ~ 23.5' x 23.6'.

The EMCCD has a quantum efficiency of ~ 90 per cent at Hα and the Electron Multiplying gain used yielded a read-out noise of σ ~ 0.05 electron. In the Photon Counting Mode, the camera is operated at a higher frame rate and only one photon per pixel can be detected, which eliminates the excess noise factor. Nonetheless, in order to lower the effect of the Clock Induced Charges generated by the Andor camera, the observations were done in Amplified Mode (15 s per image), where more than one photon per pixel per frame can be counted. This mode of operation causes the excess noise factor of the EMCCD to affect the photometric quality of the data. More details can be found in Daigle, Carignan & Blais-Ouellette (2006) and Daigle et al. (2004, 2008).

NGC 253 was observed over three fields: centre, north-east and south-west. See Fig. 3 for outlines of the fields. Each field was exposed with an exposure time of 15 seconds per channel. The central field was exposed for 64 cycles, corresponding to 640 minutes or 10.7 hours. The north-east and south-west fields were each exposed for 38 cycles, corresponding to 380 minutes or 6.3 hours.

2.2 Data reduction

2.2.1 Reduction steps

Raw observational data consist of many data files taken for every cycle and channel. Each observational run consists of one to twelve cycles, and for each run, a wavelength-sorted...
data cube can be extracted. The first step is to correct the data with the normalized flat image. In order to correct for the airmass dependance, which can vary considerably during an observing run, the correction must be applied prior to the creation of a wavelength-sorted data cube. These two corrections are applied at the beginning of the reduction procedure, for each and every channel of every cycle. The following steps were adopted for the reduction of the data:

1. Correction of all data with the normalized flat image.
2. Creation of a wavelength-sorted data cube corrected for airmass dependance, guiding shifts, cosmic rays, dark, and gain.
3. Ghosts correction (see Epinat et al. 2008).
4. Heliocentric velocity correction.
5. Hanning spectral smoothing and sky subtraction (see Daigle et al. 2006).

The data cubes were then summed for each field of NGC 253, using the position of bright stars. The three fields were then mosaicked together, and corrected for the different exposure times using the computed flux of bright stars in each field. The final data cube has 1024 × 512 pixels.

2.2.2 Lorentzian and gaussian profiles

The intensity weighted method, which is often used to extract the velocity of galaxies through spectral-line profiles, calculates the barycentre of the spectral line, and is appropriate for cases of low S/N data (see Amram 1991, for more details). However, the shape of the emission lines observed should be the result of a convolution between the device function, an Airy function, and the emitted spectral line, which is assumed to be gaussian. Thermal agitation of the gas dominates, and is responsible for the gaussian shape of the profile. The observed profile has therefore been approximated by a Lorentzian or a gaussian profile. The gaussian function, an Airy function, and the emitted spectral line, should be the result of a convolution between the device function and the filter spectrum.

2.3 Hα flux calibration

The Hα flux calibration of the data was done during the reduction process. In order to carry out the calibration, an extinction coefficient as well as a conversion factor (FAC) must be determined as defined by Eq. 1 and Eq. 2 where Flux is the corresponding flux value, X is the airmass at the time of exposure, Cobs is the observed number of counts, and Ctrue is the true number of counts. In order to alleviate the total number of parameters to adjust, the zero point parameter, B, and the initial conversion factor, fac, were combined together to obtain the conversion factor (FAC).

\[
\text{Flux} = f_{ac} \cdot C_{\text{true}} = f_{ac} \cdot 10^{\left(A \cdot X + B\right)/2.5} \cdot C_{\text{obs}} = 10^{\left(A \cdot X\right)/2.5} \cdot C_{\text{obs}} \cdot f_{ac} \cdot 10^{\left(B/2.5\right)}
\]

(1)

\[
\text{Flux} = 10^{\left(A \cdot X\right)/2.5} \cdot C_{\text{obs}} \cdot (\text{FAC})
\]

(2)

For this study, the value of the extinction coefficient published by ESO was used. The value for Hα at the La Silla site is 0.07 mag/airmass (see also Burki et al. 1993).

The next step was to extract the conversion factor between the number of counts corrected for airmass and the corresponding flux. This was accomplished once all the reduction steps were performed, and the total number of counts was obtained, since it allows a better constraint on the factor determined. The continuum subtracted Hα map from the SHASSA (Southern Hα Sky Survey) catalogue was used to flux calibrate the data (Gaustad et al. 2001, http://amundsen.swarthmore.edu/). This catalogue has units of deci-Rayleigh, dR (1R = 10^{-5}) photons cm^{-2} s^{-1} sr^{-1} or 0.6 × 10^{-17} ergs cm^{-2} s^{-1} arcsec^{-2} or to an Emission Measure, EM, of ~ 2 cm^{-6} pc). Moreover, the SHASSA image was corrected for [N II] (λλ 6548 Å, 6583 Å) contamination. For NGC 253, the intensity of the contamination was considered to be 0.48 times that of the Hα intensity (Kennicutt et al. 2008). Afterwards, a linear regression was applied between the counts observed from this study and those of the SHASSA catalogue for individual bright H II regions in NGC 253. Fig. 1 compares the calibrated data from this study with those of the SHASSA image for bright H II regions.

3 VELOCITY FIELD

The velocity field was extracted using three distinct methods. The first followed the reduction steps outlined in Section 2.3.1, and the resulting velocity field is presented in the top-left image of Fig. 2. The corresponding velocity dispersion map and Hα integrated map are also shown. As expected from an inspection of the velocity dispersion map, the velocity field contains perturbations, notably in the inter-arm region of the northern side. In order to determine the global kinematical parameters, a second method using a gaussian smoothing with w{sub}3 = 55" (20 pixels) was used to extract the velocity field, where w{sub}3 is the width in " of the smoothing function (see bottom-right image of Fig. 2). In order to study the very diffuse emission at extended radii, a third method was used to extract the velocity field. A special binning procedure similar to that used by Bland-Hawthorn et al. (1997) was applied. The smoothing function has the shape of an isosceles triangle (pie-shape), centred around the major axis of the galaxy and about its dynamical center. For a given opening angle, different regions corresponding to different radii intervals were binned together. An opening angle of ~ 15" centred around the ma-
Figure 2. Kinematical maps of NGC 253 obtained after a 5 pixels × 5 pixels square binning and a single Gaussian fitting procedure, unless otherwise specified. Top-left: Hα velocity field. Top-right: Dispersion map. Bottom-left: Flux calibrated integrated map obtained after correction for [N II] contamination (scaled in $1/6$ Rayleigh or $10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$). Bottom-right: Hα velocity field with a gaussian spatial smoothing of $w = 55''$.

Figure 1. Comparison between the fluxes obtained for NGC 253 in this study, and those of Gaustad et al. (2001). Each point represents a bright H ii region in NGC 253. The conversion factor was determined to be 4576 (1 count = 4576 dR, where $1/6R$ or an EM of $2/6$ cm$^{-6}$ pc is equivalent to $10^{-18}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$). The continuous line has a slope set to unity.

The central regions of NGC 253 are very bright. It is therefore possible that this bright source causes the appearance of parasitic emission in the field, similar to ghosts. The light from the nucleus is a strong continuum source. When passing through the filter, diffusion of the light can be observed. These ghosts will appear as rings in the velocity map, on top of the velocity field of the galaxy. The following section describes in detail this parasitic emission, as well as the method used to distinguish it from the diffuse emission of the galaxy.

4 ISOLATING THE EXTENDED DIFFUSE EMISSION

4.1 Diffuse Ionised Gas

The term DIG refers to a component of the interstellar medium that is both warm, $T \sim 6000 - 10000$ K (Reynolds 1992), and diffused, $n_e \sim 0.03$ cm$^{-3}$ (Dopita & Sutherland 2003). The DIG has low values of EM, since the emission measure depends on the square of the density. This component can be studied by separating its emission from the bright, high EM, ionised regions in a galaxy, such as H ii regions. Some have simply separated this component by applying a cut off: any emission below a certain EM, such as...
Deep Hα Observations of NGC 253

Figure 3. Top-left: Velocity field of NGC 253 obtained after a $5 \times 5$ square binning procedure, a pie-shaped binning procedure, and a single gaussian adjustment to the emission profiles. The last three binned intervals (black contours) are the result of [N\textsc{ii}] emission. Outlines of the three fields are also plotted in large squares: black for centre field, blue for north-east field and red for south-west field. Top-right: Close up of same velocity field, but without any masking applied - the rings of the parasitic emission embedded in the velocity field are clearly seen. The black annuli contours show the regions binned to extract the typical parasitic spectra. Bottom: Spectra of the last three binned intervals of the pie-shape in order of radius (from left to right). The star-like points are for the spectra of the DIG and the continuous black profile are for the corresponding typical parasitic spectra. The blue vertical line represents the location of the H\alpha line, the red vertical lines represent those of the [N\textsc{ii}] emission, and the grey regions give an indication of the location of the contaminated areas.

∼ 80 pc cm$^{-6}$ (value taken from Ferguson et al. 1996), was considered to be from the DIG.

However, Hoopes et al. (1996) argue that this simple cut off method is not adequate for highly inclined galaxies such as NGC 253, and that it can result in underestimating the total DIG component. In their study, they developed a special median filtered masking technique to isolate the DIG emission from their NGC 253 images, see Hoopes et al. (1996) for more details.

Nonetheless, the goal of this study is not to separate the DIG emission from the bright ionised regions. The goal is to obtain a very deep image of the galaxy in order to study the kinematics at very extended radii. This does not require isolating the DIG component, since any emission whether with high or low EM can be used to obtain kinematical measures.

For the extended ionised emission detected beyond ∼ 11′, we use the term DIG. It is expected that at large radii, the EM of the gas drops significantly. For radii beyond ∼ 11′ in NGC 253, the EMs are well below a few pc cm$^{-6}$, which qualifies it has DIG regardless of the inclination of the galaxy. In the following section, we explain how this very low EM gas was detected, and how its emission was isolated from the parasitic emission mentioned in Section 3.

4.2 Isolating the extended DIG emission from the parasitic emission

The parasitic emission seen in the data of this paper is thought to originate from diffusion of the bright nucleus light when passing through the filter. The same parasitic emission was seen on other observing runs, when the targets were bright point-like planetary nebulae. Since the nucleus of NGC 253 is particularly bright and point-like, the parasitic emission seen could therefore have the same cause which is thought to be diffusion of light through the filter.

The top-right panel of Fig. 3 shows a close up of the raw velocity field (no masking applied), where the parasitic emission is clearly seen as concentric circular rings embedded in the velocity field of NGC 253. The centre of the parasitic rings coincides with the FP optical centre, and so rings were seen for each field (centre, north-east, south-west).
In Fig. 2, the velocity field of the galaxy extends up to a radius of \( \sim 11\,\text{''} \). The intensity of the emission lines that gave forth to this velocity field are on average 6 times stronger than the intensity of the parasitic emission. Thus, for regions of strong H\( \alpha \) emission, i.e. up to 11\''\, the parasitic emission is not problematic since the emission lines of the gas can be easily identified. The spectrum of each pixel in this velocity field was also individually examined, and all data that did not clearly show a strong emission line were discarded.

For very low EMs, i.e. beyond a radius of 11\'', the line intensity can be as low as the intensity of the parasitic emission. Diffuse emission can therefore be hidden in the signal of the parasitic emission. However, Fig. 3 shows that the parasitic emission is not random noise; it has a well-defined spectra which gives circular rings in the velocity field. Therefore, a typical spectrum of the parasitic emission can be extracted for each radius interval, and used to identify if the emission seen is from the extended DIG or the parasitic emission.

The method used to isolate the extended DIG emission is as follows, and is similar as the one used by Bland-Hawthorn et al. (1997) to identify the DIG emission in their study. This method is applied to all radii beyond 11\'', where diffuse emission is seen. The DIG emission was extracted using a pie-shape binning procedure centred around the dynamical centre of the galaxy (see pie-shape in top-left of Fig. 3). The spectra of the parasitic emission was extracted using another pie-shape binning procedure, this time centred around the centre of parasitic rings (see pie-shape outlined by black annuli in top-right of Fig. 3). The opening angle was chosen to be large enough so that a typical signal for the parasitic emission could be extracted, while smoothing out any emission from the galaxy. The radii intervals were chosen to be the same as the first binning procedure. Any emission profiles detected in the first procedure (pie-shape centred on galaxy) and not in the second (pie-shape centred on parasitic rings) should be the result of emission from the DIG.

The bins with more than a 3\( \sigma \) detection are illustrated in the bottom panels of Fig. 3. These all lie on the receding side of the galaxy. They are the last three intervals shown with black contours in the pie-shaped velocity field and are located at 11.5\''\pm 0.6\'', 12.8\''\pm 0.7\'', 19.0\''\pm 0.9\'' (top-left of Fig. 3). In these three bins, the bottom panels of Fig. 3 show that the DIG spectra (star-like points) have an emission line (blue or red line) not seen in the corresponding typical parasitic spectra (black curve).

Different opening angles were tested for the pie-shape centred on the parasitic rings, but they always gave the same results. First, that the extracted spectra of the parasitic rings did not vary significantly, which means that the parasitic emission is not just random noise and that a typical spectra can be extracted. Second, when compared to the parasitic spectra, the DIG spectra always showed a 3\( \sigma \) detection for the same four emission lines mentioned in the previous paragraph. These emission lines lie along the major axis of the galaxy, are not from the parasitic emission, and therefore can be interpreted as emission from the DIG.

The integrated flux of the first, blue, line (\( r = 11.5\'' \pm 0.6\'' \)) gives an EM of \( \sim 0.14 \, \text{cm}^{-6} \, \text{pc} \), and those with the red line (\( r = 11.5\'' \pm 0.6\'', 12.8\'' \pm 0.7\'', 19.0\'' \pm 0.9\'' \)) give an EM of \( \sim 0.10 \, \text{cm}^{-6} \, \text{pc} \). Table 2 shows these results. The EMs were calculated by subtracting the contamination spectra from the DIG profiles, then correcting for the filter dependence and integrating the profiles. The 1\( \sigma \) upper limit for the EM is \( \sim 0.03 \, \text{cm}^{-6} \, \text{pc} \). This was calculated by taking the standard deviation (\( \sigma \)) between the spectrum resulting from the pie-shape centred on the galaxy, and that centred on the parasitic emission, for all the radii bins beyond 11\''. For the three radii bins where DIG was detected, the emission line profile was omitted before calculating \( \sigma \). From the averaged \( \sigma \), and a typical width for the extended DIG emission lines, the 1\( \sigma \) upper limit for the EMs was found to be \( \sim 0.03 \, \text{cm}^{-6} \, \text{pc} \). Hence, the three emission lines seen have EMs on the order of 3\( \sigma \). Any emission below this limit was not considered as DIG emission. The error of the emission line fluxes is thought to be on the order of \( \sigma \), therefore of \( \sim 30 \) per cent.

4.3 Nature of the emission lines

The extended DIG emission line found in the first radii interval (\( r \sim 11.5\'' \)) and identified with a blue line in Fig 3 should be the H\( \alpha \) line at \( \lambda \sim 6572 \, \text{\AA} \), according to a velocity pattern continuity argument. Due to the periodicity of FP spectrum, in this figure, the wings of this line are seen on both extremity of the spectrum. This is the phase jump effect. Phase jumps are common in FPs when the filter bandpass is larger than the FSR of the FP.

More precisely, a phase jump, also known as interorder confusion of neighbouring FP orders (see Bland-Hawthorn et al. 1992 Daigle et al. 2006), appears because the interference pattern of the FP will transmit (for a given spacing of the plates) all wavelengths \( \lambda \) such that \( \lambda = \lambda_0 \pm n \times \text{FSR} \) where \( n \) is an integer value, providing that these wavelengths are also transmitted by the interference filter used for selecting the wavelength range to be scanned with the FP and to limit the number of phase jumps (see Fig. 3). Essentially, the FP acts like a secondary filter, with a transmission peak occurring every 8.6 \( \text{\AA} \). In other words, light first travels through the interference filter, which affects the intensity of the light, depending on the transmission probability (Fig. 3). Then, light travels through the FP, where phase jumps can occur, but do not affect the intensity of the light. Therefore, the probability of having phase jumps of a specific emission line depends only on whether the probability of it passing through the interference filter is high enough.

In this study, we have chosen the most adequate interference filter to cover the wavelength range of the H\( \alpha \) line in NGC 253, given its systemic velocity and we study the FP interference order corresponding to the wavelength range between \( \sim 6564 \, \text{\AA} \) and \( \sim 6572 \, \text{\AA} \), covering H\( \alpha \) velocities between 40 and 450 \text{km s}^{-1} \) (see Section 2.1). Hence, the spectrum is plotted between 6564 \text{\AA} and 6572 \text{\AA}, but there could be emission from neighboring free spectral ranges: for instance, an emission line detected at \( \lambda = 6570 \, \text{\AA} \) could be emitted at \( \lambda = 6570 \pm n \times 8.6 \, \text{\AA} \).

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\footnote{This gave an opening angle of about 140\(^\circ\), except for the first radii bin (\( r = 11.5\'' \pm 0.6\'' \)) where a much smaller opening angle had to be chosen. An opening angle of 140\(^\circ\) would have overlapped significantly on emission from the galaxy.}
In order to derive the rotation curve of NGC 253 from the analysis of the velocity field, the GIPSY task ROTCUR (Begeman 1989) was used. The objective is to extract the orientation parameters (dynamical centre \((x_0, y_0)\), systemic velocity \(V_{\text{sys}}\), inclination \(i\) and position angle \(PA\)) that best reproduce the observed velocity field. As mentioned earlier, the velocity field smoothed with a gaussian function of \(w_\lambda = 55'\) is used. The parameters are found by a least square method between the observed velocity field and the tilted rings derived by ROTCUR.

There are three main steps with the GIPSY program. Since they are correlated, the dynamical centre and systemic velocity are found first by keeping \(i\) and \(PA\) fixed at their initial values. The initial values are the ones derived by the \(H\alpha\) study of Puche et al. (1991). Data in an opening angle of 65' around the minor axis are excluded in order to minimize errors due to deprojection effects. A cosine-square weighting function is then used on the rest of the data, maximizing the weight of the points around the major axis. From this, the dynamical centre is found to be located at \(\alpha = 00 : 47 : 35.2\) and \(\delta = -25 : 17 : 07.6\), in the World Coordinate System. A systemic velocity of \(241.2 \pm 5.4\) km s\(^{-1}\) is also found. This value is compatible with the values derived from \(H\alpha\) by Puche et al. (1991) \((\sim 245\) km s\(^{-1}\)) and from \(H\alpha\) by Bland-Hawthorn et al. (1997) \((243 \pm 9\) km s\(^{-1}\)).

The second step seeks to find the inclination \(i\) and the position angle \(PA\), while keeping the dynamical centre and systemic velocity fixed at their extracted values. The initial values for the inclination \(i\) and position angle \(PA\) are again those derived by the \(H\alpha\) study of Puche et al. (1991). Separate solutions are obtained for the receding and approaching side. A mean value for the inclination \(i\) of \(76.4 \pm 3.9'\) and for the position angle \(PA\) of \(230.1 \pm 2.1'\) are derived between a radius of \(1'\) and \(10'\). ROTCUR could not converge for a small number of radii, and the value of the parameters at these radii were extrapolated with the values of nearby data. The gaussian smoothed velocity field extends to a radius of \(10'\), while the original velocity field extends to \(11.5'\), although the latter is very clumpy beyond \(10'\). In order to derive the rotation curve from the original velocity field using the derived kinematical parameters, extrapolated values of the parameters were added for radii between \(10'\) and \(11.5'\). The top figures of Fig. 4 show the adopted values for the inclination \(i\) and position angle \(PA\). The results are consistent with the parameters derived by the \(H\alpha\) study of Puche et al. (1991), and also suggest the presence of a warp in the outer regions as seen through the decrease of the position angle at \(r \approx 5'\). In the inner \(5'\) region, a variation of the position angle is also seen. However, this can be attributed to the perturbations of the nuclear region since NGC 253 is known to be a starburst galaxy. Puche et al. (1991) find for the \(H\alpha\) data a mean inclination \(i\) of \(\sim 72'\) and a mean position angle \(PA\) of \(\sim 229'\). From the adopted values of the inclination \(i\) and position angle \(PA\) varying with radius, the rotation curve of NGC 253 could be extracted from the original velocity field (without the gaussian smoothing). The warp seen in NGC 253 (Puche et al. 1991) can be accounted for by letting the inclination and the position angle vary with radius. The bottom-left image of Fig. 4 illustrates the rotation curve.

5 KINEMATICAL PARAMETERS AND ROTATION CURVE

The DIG emission lines identified by a red line in Fig. 4 at \(\lambda \approx 6566.4\) Å cannot be from \(H\alpha\) since the velocities implied are not consistent with the velocity pattern of the galaxy. They are rather emission from the \([\text{N} \text{ii}]\) line (\(\lambda 6548\) Å) redshifted, and are probably observed around this wavelength due to a phase jump.

Fig. 4 shows the filter transmission profile, and the locations of the blueshifted and redshifted emission lines of \([\text{N} \text{ii}]\lambda 6548, 6583\) Å and \(H\alpha\) lines. This figure clearly shows that on the receding side of the galaxy (redshifted), the \([\text{N} \text{ii}]\lambda 6548\) Å line is more likely to be transmitted than the \(H\alpha\) line. The line could be emitted at 6566.4 Å or at 6557.8 Å (in case of a phase jump) or even at 6549.2 Å. Due to the interference filter transmission, this line is implied are not consistent with the velocity pattern of the galaxy. They are rather emission from the \([\text{N} \text{ii}]\) line (\(\lambda 6548\) Å) redshifted, and are probably observed around this wavelength due to a phase jump.

Figure 4. Interference filter transmission profile (black curve), shown in per cent. The positions of the redshifted (red) and the blueshifted (blue) \([\text{N} \text{ii}]\lambda 6548, 6583\) Å and \(H\alpha\) lines are also shown. NGC 253 has a systemic radial velocity of \(\sim 241\) km s\(^{-1}\). The redshifted velocities were calculated using a radial velocity of \(\sim 450\) km s\(^{-1}\) and the blueshifted velocities were calculated using a radial velocity of \(\sim 40\) km s\(^{-1}\). As can be seen, the redshifted \([\text{N} \text{ii}]\lambda 6548\) Å is almost perfectly transmitted, much more than the redshifted \(H\alpha\) line. The FSR of the FP (8.6 Å) is also shown in the upper-left corner.
The study by Dicaire et al. (2008) found an extended $\text{H} \alpha$ rotation curve for NGC 7793, another galaxy of the Sculptor group. The $\text{H} \alpha$ emission extended out to the $\text{H} \alpha$ isophotes showed distortions in the inner regions, but were symmetric out to 13′ (see the near-UV contours shown in Fig. 5). This suggest, that at least for the two inner bins where we detected diffuse gas ($r = 11.5′, 12.8′$), we can treat the rotation as been circular. For the outermost point ($r = 19.0′$), our observations do not allow us to make a definitive answer.

A deep optical image of NGC 253 was taken by Malin & Hadley (1997), and is presented in Fig. 2 of Boomsma et al. (2005). This image supports the idea that the stellar disc of NGC 253 extends well beyond the $\text{H} \alpha$ disc, while the image also suggests that there are some disturbances on the south-west side of the galaxy. This could contradict the results regarding the Galex isophotes. However, we prefer to keep with the assumption of circular orbits as in Bland-Hawthorn et al. (1997)’s paper, and see what kind of results we obtain.

The adopted values of the rotation velocity and the associated errors are given in Table 2 and Table 3. In order to compare our results, with the previous ones, the $\text{H} \alpha$ rotation curve found by Puche et al. (1991), is illustrated in Fig. 5, as well as the extended data points found by Bland-Hawthorn et al. (1997), where the inclination and systemic velocity of this study were used. For the later, see Table 3. Finally, the $\text{H} \alpha$ rotation curve derived by Arnaboldi et al. (1995), using long-slit observations, is also illustrated in the figure. The latter study did not correct the rotation curve for the inclination or the PA, and therefore did not consider the variation in the kinematical parameters with radius. Deviations are therefore expected. Their curve, plotted in Fig. 5, has been corrected for inclination using the mean value derived for our study.

Table 2. Adopted $\text{H} \alpha$ rotation curve

| radius (arcsec) | $V_{\text{rot}}$ (km s$^{-1}$) | $\Delta V_{\text{rot}}$ (km s$^{-1}$) | radius (arcsec) | $V_{\text{rot}}$ (km s$^{-1}$) | $\Delta V_{\text{rot}}$ (km s$^{-1}$) |
|----------------|-------------------------------|-------------------------------|----------------|-------------------------------|-------------------------------|
| 60             | 123.96                        | 35.66                         | 390            | 183.09                        | 19.21                         |
| 90             | 124.54                        | 9.97                          | 420            | 182.45                        | 22.31                         |
| 120            | 161.25                        | 4.97                          | 450            | 185.27                        | 20.80                         |
| 150            | 189.73                        | 6.71                          | 480            | 198.82                        | 9.74                          |
| 180            | 201.20                        | 3.50                          | 510            | 199.55                        | 4.01                          |
| 210            | 197.36                        | 2.82                          | 540            | 203.52                        | 1.54                          |
| 240            | 192.80                        | 10.79                         | 570            | 202.81                        | 10.88                         |
| 270            | 187.55                        | 13.65                         | 600            | 212.54                        | 9.65                          |
| 300            | 170.12                        | 30.85                         | 630            | 212.72                        | 11.67                         |
| 330            | 160.46                        | 36.60                         | 660            | 208.00                        | 13.81                         |
| 360            | 168.38                        | 32.31                         | 690            | 197.72                        | 18.30                         |

6 MASS MODELS

In order to determine the impact of the DIG component velocity points at large radii, two mass models analysis have been obtained for NGC 253. The first has been performed on the data taken without the three points of the DIG while the second included those extended velocities. Furthermore, in order to compare our results with those found for the $\text{H} \alpha$ data by Puche et al. (1991), the analysis of the mass distribution must be the same. Hence, another mass model analysis has been obtained using the data taken from Puche et al. (1991). A dark halo represented by an isother-
Figure 6. Top: Kinematical parameters of NGC 253 derived from the gaussian smoothed ($w_{\lambda} = 55''$) velocity field for both sides (circles) and separately for the receding (red triangles) and for the approaching (blue triangles) sides. The non-filled symbols represent the extrapolated parameters, see Section 4 for more details. Bottom-left: Rotation curve derived using the kinematical parameters of the top figures as a function of radius, with a systemic velocity of $V_{sys} = 241.2$ km s$^{-1}$, and the non gaussian smoothed velocity field. The rotation curve obtained using both sides at once is represented by the continuous line, along with the derived error bars, while the receding (red) and approaching (blue) sides are represented by the triangles. Bottom-right: Final adopted rotation curve, with the proper error bars as explained in the text (continuous line). The slashed line represents the H$\alpha$ data from Puche et al. (1991), and the double-dot slashed line represents the H$\alpha$ data from Arnaboldi et al. (1995). The colored points illustrate the results of Bland-Hawthorn et al. (1997) for [N$\Pi$] (orange squares) and for H$\alpha$ (green circles) beyond the H$\iota$ data, as well as those derived from this study (blue and red diamonds).

Table 3. Derived DIG rotation velocities and those of Bland-Hawthorn et al. (1997)

| This Study | radius (arcsec) | $\Delta r$ (arcsec) | $V_{rot}$ (km s$^{-1}$) | $\Delta V_{rot}$ (km s$^{-1}$) | $EM$ cm$^{-6}$ pc |
|------------|-----------------|---------------------|-------------------------|-----------------------------|------------------|
| BH 1997    | 690             | 36                  | 200.51                  | 33.10                       | 0.14             |
|            | 690$^a$         | 36                  | 226.64                  | 23.60                       | 0.10             |
|            | 768$^b$         | 42                  | 187.06                  | 13.90                       | 0.10             |
|            | 1140$^b$        | 51                  | 150.98                  | 15.25                       | 0.10             |

$^a$ H$\alpha$

$^b$ [N$\Pi$]

Three parameters must be specified: two for the dark halo, namely a one-dimensional velocity dispersion $\sigma$ and a core radius $r_c$, related together by the central density $\rho_0 = 9\sigma^2/4\pi Gr_c^2$, and the mass-to-light ratio ($M/L_\star$) of the stellar disc. The papers by Carignan & Freeman (1985) and Carignan (1983), show in greater detail the method used. A least square fit is applied to determine the three parameters. In order to compare with the H$\iota$ study, the stellar disc is described by the surface brightness profile in the $B$ band, as in Puche et al. (1991). The gaseous component is also taken as the one derived in the H$\iota$ study. The latter includes the 4/3 multiplication factor to account for the H$\alpha$ contribution.

The mass model is designed to put higher weight on...
Figure 7. Mass model analysis for the adopted H\textsubscript{i} rotation curve (star-like points) of NGC 253. The data were taken from Puche et al. (1991). An isothermal sphere was used for the dark halo. A first analysis was performed using a maximum stellar disc (top), and a second using a sub-maximum stellar disc (bottom). The stellar disc is plotted with a small-dashed line, the gaseous component with a dot-dashed line, the halo with a long-dashed line and the total adjusted rotation curve with the continuous line. The parameters extracted are in Table 4.

On the other hand, the data points that have small errors. In the case of the H\textsubscript{i}, the data at intermediate radii, between 3 and 5.5 kpc, have much smaller errors than the central and outer points. On the other hand, in the case of the H\alpha data, the mass model tended to fit as best as possible the central areas which had the smallest errors. This yielded very different results. Hence, in order to better compare the H\textsubscript{i} and the H\alpha data, equal weight was given to all data points.

First, a maximum disc model with no halo component was obtained (see top of Fig 7). Second, a sub-maximum disc was obtained. Here, (M/L), is fixed to the value that allows the maximum velocity of the stellar disc to be 0.6 times the maximum velocity of the rotation curve (H\textsubscript{i} or H\alpha) as suggested by the study of Courteau & Rix (1999). Indeed, (M/L), determined from the maximum disc is usually too high to agree with the predictions of the stellar populations models (Bell & de Jong 2001). See bottom of Fig 7 and Table 4.

Table 4. Mass models for NGC 253

|               | H\textsubscript{i} RC\textsuperscript{a} | 36-cm H\alpha RC without DIG | 36-cm H\alpha RC with DIG |
|---------------|--------------------------------------|-------------------------------|---------------------------|
| Max Disc      |                                       |                               |                           |
| (M/L)\textsuperscript{b} | 12.0                                 | 12.9                          | 12.5                      |
| Dark halo\textsuperscript{c} | none                                 | none                          | none                      |
| Sub-Max Disc  |                                       |                               |                           |
| (M/L)\textsuperscript{b} | 5.0                                  | 5.0                           | 5.0                       |
| Dark halo     | r\textsubscript{c} = 2.3              | r\textsubscript{c} = 1.0      | r\textsubscript{c} = 1.0   |
|               | \sigma = 2.72                         | \sigma = 3.04                 | \sigma = 2.99             |
|               | \rho\textsubscript{0} = 0.286         | \rho\textsubscript{0} = 1.579 | \rho\textsubscript{0} = 1.564 |

\textsuperscript{a} Puche et al. (1991)
\textsuperscript{b} in units of M\odot/L\odot
\textsuperscript{c} r\textsubscript{c} in kpc, \sigma in km s\textsuperscript{-1}, and \rho\textsubscript{0} in M\odot pc\textsuperscript{-3}
Figure 9. Mass model analysis for the adopted Hα rotation curve with the DIG [N II] + Hα points (star-like points) of NGC 253. Same caption as Fig. 9 with a maximum stellar disc (top) and a sub-maximum stellar disc (bottom). The H I data from Puche et al. (1991) are also plotted with the diamond-shaped points.

7 ANALYSIS OF THE RESULTS

7.1 Nuclear region

NGC 253 is a starburst spiral galaxy. The central regions have been thoroughly studied. Some suggest that NGC 253 is also an AGN (Ptak et al. 1997) and has extensive galactic winds (see a review by Veilleux, Cecil & Bland-Hawthorn 2004). The paper by Heesen et al. (2009) also finds that the poloidal component of the magnetic field shows a prominent X-shaped structure centred on the nucleus. Boomsma et al. (2002) also find extra-planar H I on the north-east half of the galaxy, in the shape of a half-ring structure and plumes, with a smaller rotation velocity than the disc. It is suggested that the origin of the extra-planar H I is related to the starburst activity and the active star formation in the disc.

The present study finds high Hα emission and high velocity dispersions in the nuclear region, which are expected from the strong nuclear activity. Higher-resolution data have also seen a large dispersion in the velocity field (see Zhao et al. 2001), which suggest that the one found in this study is not due to beam smearing. A small bar-like structure is also seen in the velocity field, lagging in velocity by at least 50 km s$^{-1}$ (see top-left image of Fig. 2) the bar-like structure in the nuclear region appears more blue-shifted than its surroundings. The structure also seems slightly inclined with respect to the major axis. The dimensions are approximately 24′′ by 88′′, i.e. 0.3 kpc by 1.1 kpc. The strong activity in the nuclear region of the galaxy could account for these observations, including the presence of a possible bar (Paglione et al. 2001) or a possible counter-rotating circumnuclear disc (Zhao et al. 2001). An inclined counter-rotating disc could be overlaying the bulk circular rotating disc and account for the lagging velocities and strong dispersion. Rubin, Graham & Kenney (1992) and Rix et al. (1992) have shown for the early-type galaxy NGC 4550, that a natural explanation for a decrease in velocities and increase in dispersion could be the presence of two counter-rotating stellar components, as indicated by the observed double-peaked line profiles. Although NGC 253 is not an early-type galaxy, but a late-type, this explanation could also be appropriate for its gaseous component.

In Fig. 9, the Hα rotation curve derived from this study is seen to agree well with the H I rotation curve derived by Puche et al. (1991), except for the inner regions. Here, the Hα slope is much steeper. This can be understood since the H I data is of much lower resolution ($\sim 68′′$) compared to the Hα data ($\sim 2.8′′$), and beam smearing is expected which causes the inner slope to be less steep. Hence, an important advantage is that Hα data probes more accurately the inner regions of the rotation curve.

7.2 Diffuse Ionized Gas

7.2.1 [N II] and Hα emission

This study succeeded in detecting the [N II] ($\lambda 6548$ Å) emission on the receding side of NGC 253 at radii of 11.5′, 12.8′ and 19.0′, as well as Hα emission on the receding side at a radius of 11.5′. The details concerning the identification of extended DIG emission are described in Section 4.

No [N II] emission was seen on the approaching side. The 3σ upper limit for the EM is $\sim 0.09$ cm$^{-6}$ pc (see Section 4). The presence of the [N II] emission on the receding side could be the result of a phase jump in the emission line, and the detection was just above a 3σ detection. Fig. 9 shows that the filter transmission on the receding side was almost maximal for the [N II] line, about 80 per cent. However, on the approaching side, the transmission of this line drops down to 50 per cent, which would make the 3σ detection difficult. This could explain why no emission of this line was seen on the approaching side.

For the receding side, no [N II] emission was seen between 12.8′′ ± 0.7′′ and 19.0′′ ± 0.9′′. No significant 3σ nor even 2σ detection was seen. Between these radii, the parasitic emission varied more, i.e. was noisier. Since the [N II] emission that was detected ($r = 11.5′$, 12.8′, 19.0′) was already difficult to detect, being just barely above a 3σ level, the noisier parasitic emission could explain why no [N II] was detected between 12.8′ and 19.0′. Another explanation could be that the DIG is in the form of discrete clouds, which would mean that emission from it can only be seen at discrete radii. Even if these clouds are embedded in a diffuse background, the EMs from this background might be too low to be detected.

A question remains unanswered. It concerns the Hα emission. In the pie-shape procedure, Hα was detected up...
to a maximum radius of 11.5′ ± 0.6′, which coincides with the maximum radius of the Hα study of Puche et al. (1991). The strength of the diffuse emission line in this radii bin (receding side, r = 11.5′) is about a factor of 10 lower than the strength of the line in the previous radii bins. No Hα emission is observed beyond, on both sides of the galaxy. Fig. 4 shows that for Hα, the transmission probability is only about 50 per cent for the receding side, and about 80 per cent for the approaching side. Hence, detecting Hα emission beyond the H1 is much more probable on the approaching side with the observing tools of this study, and yet, no 3σ detection was seen.

Bland-Hawthorn et al. (1997) mention the possibility that their detections on the receding side could be explained by accretion of a faint gas-rich object at large radius. This is supported by an image only showing extended stellar light at large radii on the receding side (see Bland-Hawthorn et al. 1997, for more details). This could explain why no extended DIG was seen on the approaching side.

Considering that we were only able to detect emission at specific radii and not continuously across all radii, the clumpiness of the gas would argue for an accretion phenomenon. It has been suggested that the extended disc in M31 is the result of accretion (Ibata et al. 2002; Peñarrubia et al. 2004). Also, as mentioned in Section 4.3., the [NII] line we see at 6566.4 Å and could be an extremely redshifted line with a radial velocity of ~ 850 km s⁻¹, which would again argue for accretion of a gas rich object onto the galaxy.

However, our observations do not entirely support this idea. First, the fact that emission was only seen along the major axis argues that this emission could be associated with the galaxy. Second, as mentioned earlier, the isophotes in the UV GALEX images are symmetric out to r = 13′. If there was an accretion phenomenon, the isophotes would have been disrupted. This is supported by the isophotes in the B band image taken from the Digitized Sky Surveys. Images of this survey were taken from the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. These isophotes also extend until r = 13′ and remain symmetric in the outer radii. Third, our Hα rotation curve is consistent with the H1 rotation curve. Both curves seem to behave normally at extended radii, supporting the idea that their are no major disruptions. Fourth, the rotation velocity we obtain for the diffuse Hα emission at r = 11.5 is consistent with that of the phase jumped [NII] emission at the same radius. The [NII] emission therefore seems to trace the same rotation as Hα. If the Hα is not disrupted up until 11.5′, then the [NII] emission shouldn’t be, at least for the bin at 11.5′.

For the reasons mentioned above, we make the assumption that the extended diffuse gas we detected is truly associated with the galaxy, and that the [NII] emission we see at 6566.4 Å is the result of a phase jump, making its velocity (~ 400 km s⁻¹) consistent with the Hα velocity field.

The study by Kennicutt et al. (2003) found a mean [NII]/Hα ratio of 0.48 for NGC 253, which includes the [NII] lines at 6548 Å and 6583 Å. However, many studies have shown that this ratio can significantly change in areas located outside of dense HII regions and where the DIG component is still present (Reynolds et al. 1992; Rand 1999), i.e., at radii larger than the neutral component for NGC 253. [NII] is a forbidden line, and can therefore be seen in areas of diffuse gas where spontaneous emission can become important. Rand (1997) and Rand (1998) showed for the galaxy NGC 891 that the [SII]/Hα, [NII]/Hα and even [OIII]/Hα ratio increase significantly with increasing distance to the midplane. For the DIG component of the Milky Way, the forbidden lines of [NII] and [SII] were also found to have intensities with respect to the Hα line of a few tenths to unity, and even larger (Haffner et al. 2009). This is much greater than that observed in classical HII regions. Hence, forbidden lines could be better probes of the extended disc. This could explain the detection of [NII] at radii larger than 11.5′ rather than Hα.

The following paragraphs compare the results found in this paper with those of Bland-Hawthorn et al. (1997). Table 3 shows the EM values for the diffuse Hα and [NII] lines, both for this study and that of Bland-Hawthorn et al. (1997). The error of the flux values of our study are estimated to be 30 per cent. The flux values for the diffuse emission in Bland-Hawthorn et al. (1997)'s paper are given in milli-Rayleigh (mR). The SHASSA survey, used to calibrate our data, adopts the conversion that 1R is equal to an EM of ~ 2 cm⁻³ pc. We have used this conversion throughout this paper. From this conversion, the Bland-Hawthorn et al. (1997) fluxes give the EM values shown in Table 3. The EMs found in this study are therefore consistent with those found by Bland-Hawthorn et al. (1997).

Bland-Hawthorn et al. (1997) used the TAURUS-2 FP interferometer at the 3.9m Anglo-Australian Telescope for their observations on NGC 253. Four fields, each of 5′ each, were observed on the receding side of the galaxy. They used the FP Staring technique, which gave a single, very deep spectrum of a diffuse source for each field of view. The spectrum in a 40 Å band is spread out radially from the optical axis across the field. This means, that for the spectrum obtained at each field, an emission line seen at a wavelength is an emission line coming from a precise radius in the field. They were able to see the Hα and [NII] (6548 Å) line, with a total of 10 velocity measurements on their rotation curve. Two fields were placed at extended radii - the first was exposed for 9 hr and led to a [NII] velocity measurement at 10.5′ and a Hα velocity measurement at 12′; the second was exposed for 5 hr and led to a [NII] velocity measurement at 13.5′ and a Hα velocity measurement at 15′. The velocities found for the very extended and diffuse emission are shown in Table 3 corrected for the systemic velocity and inclination found in this study.

In Bland-Hawthorn et al. (1994), they demonstrated that the TAURUS-2 FP interferometer could reach an Hα EM of 0.02 cm⁻³ pc at the 3σ level in 6 hr across the full FSR (57 Å, in their study). Our calculations gave a 1σ upper limit for the EM of ~ 0.03 cm⁻³ pc (see Section 4), and we observed the receding side of the galaxy for a total of 6 hours. Our study therefore was not as deep as that of Bland-Hawthorn et al. (1994), but was deep enough to detect extended EMs and went further out.

According to Table 3 and the bottom-right panel of Fig 3 our velocity measurements are consistent with those of Bland-Hawthorn et al. (1994), within the allowed error bars, except for two discrepancies. First, no Hα emission was seen in our study at 15′, whereas Bland-Hawthorn et al. (1994) found emission at that radius (EM of 0.08 cm⁻³ pc). This
EM is below our 3σ detection and it is possible that our detection limits were not sufficient to allow this detection.

Second, our [N\text{ii}] velocity measurement at 12.8 ± 0.7 km s\(^{-1}\) is lying below the rotation curve found by Bland-Hawthorn et al. (1997), and more precisely below the [N\text{ii}] velocity measurement of Bland-Hawthorn et al. (1997) at 13.5 km s\(^{-1}\). The disagreement between the velocities arises from different radial velocity measurements, with a ∼ 20 km s\(^{-1}\) difference. Although the observations are made with a Fabry-Perot in both cases, the technique is not at all the same since there is no scanning in Bland-Hawthorn et al. (1997) observations. This enables to detect faint fluxes of emission lines with much more confidence but is less accurate for measuring the velocities since inhomogeneities in the galaxy (such as knots) can bias the result because they can show up even if their position in the field is not the right one for producing a constructive interference pattern. As a result it seems that the error bars on the [N\text{ii}] velocity points of Bland-Hawthorn et al. (1997) are optimistic and underestimated. It is probable that the right value of the rotation velocity of NGC253 at about 13′ radius is intermediate between the value found by Bland-Hawthorn et al. (1997) and our value, say around 210 km/s, hence in continuity with the H\alpha values found by Bland-Hawthorn et al. (1997) at 12′ and 15′ radius.

7.2.2 Origin of the very extended DIG

Hoyle & Ellis (1963) mentioned for the first time the existence of a diffused matter of free electrons in the vicinity of the Galactic plane using a low frequency synchrotron survey. Since then, many new properties of the DIG have been discovered. Some of these properties include the high ratios of forbidden lines with respect to H\alpha (Rand 1997, 1998). Furthermore, it was found that several edge-on less active galaxies show a correlation between the DIG in the halo and the star formation rate (SFR) (Rossa & Dettmar 2003, 2004; Miller & Veilleux 2003). The study by Rossa & Dettmar (2003a) also suggested that there was a minimum SFR per area required to mimic the disc-halo interaction. However, a more recent study from Dev et al. (2007) concluded from their SINGS H\alpha Survey (Survey for Ionization in Neutral Gas Galaxies) that the DIG does not seem to correlate neither with the Hubble type nor with the total SFR of the galaxy.

Nevertheless, many theories were proposed to explain the existence of the DIG. Bland-Hawthorn et al. (1997) analysed the case of NGC 253. Several ionization and heating sources for the DIG were examined, including the following: metagalactic ionizing background, compact halo sources, compact disc sources (white dwarf population and hot horizontal-branch stars), ram pressure heating resulting from shock waves, exotic heat sources such as turbulent MHD waves, young stellar disc, dilute photoionization, gas-phase depletion from grains, Lyman continuum (Lyc) ionizing photons escaping from OB stars. However, the only possible source that could explain the observations was the one regarding hot young stars in the central regions of the galaxy looking out towards the outer part of the warped disc. Ionizing photons could escape from these stars through dust scattering, and would be more easily exposed to the outer regions because of the warped structure. This explanation is in agreement with the detection of both UV emission (providing hot stars) out to r = 13′ (see Section 5) and diffuse ionized emission at r = 11.5′, 12.8′, 19.0′.

The calculations by Bland-Hawthorn et al. (1997) also ruled out the source from the metagalactic ionizing background. Their study determined that the metagalactic ionizing background was around five times less than that required to explain the H\alpha observations. Their calculations also showed that the photoionization model, accounting for the Lyc photons escaping from OB stars, could not account for the observations, since the observed ratio of [N\text{ii}] (λ 6548 A)/H\alpha was slightly higher than unity. This implies that the ratio of [N\text{ii}] (λ 6583 A)/H\alpha was close to three. The latter is twice as high as what was predicted by the photoionization model. The photoionization model also fails to explain the lack of He\text{i} (λ 5876 Å) emission. Studies show that the ionizing flux necessary to explain the observed [N\text{ii}] and [S\text{ii}] of the DIG should allow the existence of the He\text{i} line (Domgorgen & Mathis 1994).

Other studies have also shown a correlation between the DIG in the haloes of galaxies and their synchrotron radio-continuum. This might suggest that the DIG is correlated with cosmic rays and magnetic fields (see Dahlem, Lisenzfeld & Golla 1993). However, Sciana (1992) discussed that it was difficult for cosmic rays to penetrate clouds of gas, and that they should not play an important role in generating the DIG. Nevertheless, the Symposium paper by Heesen et al. (2009) found a total equipartition magnetic field on the order of 7 μG to 18 μG for the disc of NGC 253. These values remain high. The magnetic field of NGC 253 could therefore play a key role in understanding the DIG component. The presence of a disc wind in NGC 253 was also discussed in the paper by Heesen et al. (2009), and could explain the presence of extra-planar H\text{i}, H\alpha, and soft X-ray emission in the halo. Finally, it is also important to note that the Magellanic streams cannot explain the [N\text{ii}] emission found in this study, since the radial velocities of the two do not correlate spatially (Mathewson & Ford 1984).

7.3 Consequences of a declining rotation curve

Declining rotation curves in spiral galaxies are rare. However, some have been seen in earlier-type systems (Casertano & van Gorkom 1991), as well as in the edge-on Sc galaxy NGC 891 (Sancisi & Allen 1973). The Gassendi H\alpha survey of SPirals (GHASP) also find a sub-sample of galaxies showing rotation curves slightly declining (see Garrido et al. 2002, 2004, 2005; Epinat et al. 2003). Moreover, Dicaira et al. (2008) find, for the late-type system NGC 7793, a decline of ∼ 25 per cent \(v_{\text{max}}\) over half the radius range. For NGC 253, Bland-Hawthorn et al. (1997) find a decline at the last observed point of the rotation curve of ∼ 10 per cent \(v_{\text{max}}\) over the last ∼ 10 per cent of \(r_{\text{max}}\). This study finds a decline of ∼ 30 per cent \(v_{\text{max}}\) over slightly more than half the radius range. The only way not to have a declining rotation curve would be if the inclination was smaller by 30° for the last observed velocity point, which is quite unlikely (see Fig. 4).

The top panels of Fig. 4, Fig. 8 and Fig. 9 show the results for the maximum stellar disc model, respectively for the H\text{i} data of Puche et al. (1991), the H\alpha data without the DIG points, and the H\alpha data with the DIG points. In all cases, the observed rotation curve can be reproduced by a
stellar disc and a gaseous disc. Hence, no dark halo seems to be needed. However, in the central regions of the Hα rotation curve, the presence of a bulge can be observed as seen by the bump in the curve. To reproduce well this region, a bulge component could be added to the maximum stellar disc model.

An advantage of maximum disc models is that a unique solution can be determined, whereas many degeneracies exist in multicomponent fits including dark haloes (Carignan & Freeman 1985; van Albada & Sancisi 1980). Maximum stellar discs also seem to reproduce well the small scale irregularities in the rotation curves, since the stellar disc also traces these perturbations (Freeman 1992). However, as can be seen in Table 4, the (M/L)$_i$, that best fits the maximum-disc model is of $\sim 12$ M$_\odot$/L$_\odot$ for all three cases. This value is much too high, especially in the case of late-type galaxies such as NGC 253, which causes great concern for the validity of the model.

The study by Courteau & Rix (1999) showed that the Tully-Fisher relation (TFR) seemed to be independent of surface brightness for high surface brightness (HSB) galaxies when plotted as $M_V$ versus $V_{2.2}$ ($V_{2.2}$ is the velocity for an exponential disc at 2.2 scale lengths). In order to reproduce this feature, their models suggested that discs were sub-maximum with $v_{\text{disc}}/v_{\text{total}} \sim 0.6$. Additionally, their study suggested that these sub-maximum discs allowed a smooth transition between HSB and low surface brightness galaxies, and that maximum discs for the majority of the HSB late-type galaxies are not valid.

The bottom of Fig. 7, Fig. 8 and Fig. 9 show the results for sub-maximum discs, respectively for the Hα data of Puche et al. (1991), the Hα data without the DIG points, and the Hα data with the DIG points. For NGC 253, the (M/L)$_i$, was fixed to 5.0 M$_\odot$/L$_\odot$ to allow $v_{\text{disc}}/v_{\text{total}} \sim 0.6$. For all three cases, the sub-maximum disc seems to agree well with the derived rotation curves. The decline observed with the DIG points is also well reproduced. The model also yields very similar dark halo parameters for the rotation curve with and without the DIG component. Hence, the derived rotation curve for NGC 253 using the DIG points truly seems to illustrate a declining rotation curve, and hints that the end of the mass distribution has started to be probed.

Moreover, the sub-maximum disc gives a steeper slope in the central areas which seems to reproduce better the Hα data at these radii. Table 4 shows that the Hα data have a higher central dark halo density than the H1 data, which can be explained by the steeper slope of the Hα data. However, the dark halo velocity dispersion $\sigma$ seems to be fairly the same in all three cases. This parameter is a measure of the maximum amplitude of the rotation curve (Blais-Ouellette et al. 1999), and since the maximum velocity is essentially the same for the H1 and Hα data, similar values are expected. Finally, the (M/L)$_i$ in the B band expected from stellar population models, using the (B-V) given by the RC3 catalogue (0.85 mag), is $\sim 3.46$ M$_\odot$/L$_\odot$ (Bell & de Jong 2001). This is much more consistent with the ratio used for the sub-maximum disc than the one determined from the maximum disc.

Our results supports Bland-Hawthorn et al. (1997)'s suggestion that the rotation curve is declining in the outer parts. While their data points were showing a decline between 8 and 9.5 kpc, our outermost velocity point shows that the decline seems to continue out to $\sim 14$ kpc. As seen in the mass model analysis, there are two possible interpretations: 1- either the halo is truncated or 2- the halo is highly concentrated (see fig. 7, with $r_c \sim 1$ kpc). Although the second interpretation is not favoured in view the mass distribution usually seen in late-type spirals were $r_c$ is more of the order of 5-10 kpc (see e. g. Spano et al. 2008), it seems to be the right one since Fig. 10 (cumulative mass curve of the dark halo as a function of radius) shows that the halo is not truncated since it is continuously rising. This profile was derived using the parameters found with the extended Hα rotation curve.

NGC 253 is the second late-type spiral in the Sculptor group with NGC 7793 (Dicaire et al. 2008) that shows a declining rotation curve in the outer parts. For NGC 253 and NGC 7793, the halo maximum radius seem to be $\sim 10$ kpc. This is smaller than the maximum radius of $\sim 40$ kpc suggested by a dynamical analysis of the Sculptor Group (Puche & Carignan 1991). However, this study was assuming that the Sculptor group was virialized which is not necessarily the case since the crossing time is of the same order as a Hubble time. If the group is not virialized, their estimate would then be an upper limit.

8 CONCLUSION

Deep FP Hα observations were obtained for one of the Sculptor Group galaxies, NGC 253. The main conclusions of this study are as follows:

1. The velocity field was obtained using three methods. The first lead to an initial velocity field reaching a distance of 11.5′. The second, in order to extract the global kinematical parameters, used a gaussian smoothing function ($w_\lambda = 55''$)
and lead to a velocity field reaching 10\′. The third used a pie-shape smoothing, in order to extract the profiles of the DIG component. Typical flux values of \( \sim 0.1 \text{ cm}^{-2} \text{ pc} \) were reached.

2. The nuclear region showed the presence of a bar-like structure lagging in velocity and showing an increase in dispersion.

3. The observations allowed the detection of the DIG component through H\( \alpha \) emission at a radius of 11.5′ and [N\( \text{II} \)] emission at radii of 11.5′, 12.8′ and 19.0′, on the receding side of the galaxy. No H\( \alpha \) emission was observed at radii larger than the neutral component (11.5′).

4. From the gaussian smoothed velocity field, the global kinematical parameters were derived and yielded a mean systemic velocity of 241.2 ± 5.4 km s\(^{-1}\), an inclination \( i \) of 76.4 ± 3.9° and a position angle PA of 230± 2.1°. A warp is also seen through the variation of the kinematical parameters with radius.

5. A rotation curve was extracted using those global kinematical parameters and the initial velocity field. This rotation curve is in good agreement with the H\( \alpha \) curve derived by Puche et al. (1991), although the slope of the inner region is steeper (as expected from the beam smearing of the H\( \alpha \) data). The data points resulting from the extended diffuse gas (H\( \alpha \); [N\( \text{II} \)] (\( \lambda 6548 \) Å) were added and showed a significant decline although slightly different from the results of Bland-Hawthorn et al. (1997).

6. A mass model analysis was obtained for the H\( \alpha \) rotation curve with and without the velocities derived for the extended DIG emission. The two yielded very similar results, both for the maximum stellar disc and the sub-maximum stellar model. The declining part of the rotation curve was also very well modeled, and seems to truly be declining.

Deep observations of galaxies can yield very interesting results, as was the case for the study by Dicaire et al. (2008) which allowed confirmation of a truly declining rotation curve of NGC 7793. In this study, the emission detected in NGC 253 of the DIG confirmed the declining nature of the rotation curve. This has profound consequences on the study of dark matter properties, and could allow very good constraints of the parameters of the dark halo.

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