Two-dimensional H\(\alpha\) kinematics of bulgeless disc galaxies

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ABSTRACT
We present two-dimensional H\(\alpha\) velocity fields for 20 late-type, disc-dominated spiral galaxies, the largest sample to date with high-resolution H\(\alpha\) velocity fields for bulgeless discs. From these data, we derive rotation curves and the location of the kinematic centres. The galaxy sample was selected to contain nucleated and non-nucleated galaxies (as determined from prior Hubble Space Telescope imaging), which allows us to investigate what impact the gas kinematics in the host disc have on the presence (or absence) of a nuclear star cluster. In general, we find that the velocity fields span a broad range of morphologies. While some galaxies show regular rotation, most have some degree of irregular gas motions, which in nearly all cases either can be attributed to the presence of a bar or is connected to a rather patchy distribution of the H\(\alpha\) emission and the stellar light. There appears to be no systematic difference in the kinematics of nucleated and non-nucleated discs. Due to the large fields of view of the integral field units we use, we are able to observe the flattening of the rotation curve in almost all of our sample galaxies. This makes modelling of the velocity fields relatively straightforward.

Due to the complexities of the velocity fields, we obtain reliable determinations of the kinematic centre for only six of our 20 sample galaxies. For all of these, the locations of the nuclear star cluster/photometric centre and the kinematic centre agree within the uncertainties. These locations also agree for seven more objects, despite considerably larger uncertainties as to the accuracy of the kinematic centre. If we disregard all kinematically irregular galaxies, our study concludes that nuclear star clusters truly occupy the nuclei, or dynamical centres, of their hosts. Our results are thus consistent with in situ formation of nuclear star clusters. Yet, many well-motivated formation scenarios for nuclear clusters invoke off-centre cluster formation and subsequent sinking of clusters due to dynamical friction. In that case, our results imply that dynamical friction in the centres of bulgeless galaxies must be very effective in driving massive clusters to the kinematic centre.

Key words: techniques: imaging spectroscopy – galaxies: bulges – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: spiral – galaxies: star clusters: general.

1 INTRODUCTION
What defines the centre of a galaxy? This question is not merely academic, because throughout the last decade, a number of studies have found tight correlations between the global properties of galaxies and the properties of their nuclei (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Marconi & Hunt 2003; Häring & Rix 2004). These global-to-nuclear scaling relations can be interpreted such that the mass assembly of a galaxy is pre-determined by its nuclear properties or, alternatively, that galaxy nuclei evolve in a way that is governed by the assembly of the entire galaxy.

Either way, characterizing the nuclear properties has become an important diagnostic tool in constraining the formation...
mechanism(s) of galaxies. The question of where the galaxy nucleus – i.e. its centre of mass – is located seems obvious in ellipticals and bulge-dominated spirals, where very often a luminous active galactic nucleus (AGN) marks the location of a super-massive black hole which almost certainly marks the bottom of the potential well.

However, in the latest Hubble types, i.e. in bulgeless, 'pure' disc galaxies, (luminous) AGN are rare (Satyapal et al. 2009), and it is less obvious whether the galaxy disc rotates around a nucleus that follows in any way the scaling relations mentioned above. A number of recent studies have suggested that in late-type spirals, the nucleus is marked by a massive stellar cluster (Phillips et al. 1996; Carollo, Stiavelli & Mack 1998; Matthews et al. 1999; Böker et al. 2002, 2004). Such nuclear clusters (NCs) are also present in earlier type galaxies (e.g. recently Balcels et al. 2003; Lotz, Miller & Ferguson 2004; Côté et al. 2006), but the exact relation between NCs in galaxies of different Hubble types remains unclear to date. NCs have masses of \( \sim 10^8 - 10^9 M_\odot \) (Walcher et al. 2005) and show stellar populations of multiple ages (Rossa et al. 2006; Seth et al. 2006; Walcher et al. 2006), pointing towards them having a complex formation history.

On average, the location of NCs appears to coincide with the photometric centre (PC) as derived from isophotal fits (Böker et al. 2002). However, the often irregular and asymmetric shape of late-type disc galaxies causes rather large uncertainties in defining the PC, and doubts have been raised on whether NCs actually define the bottom of the potential well (Matthews & Gallagher 2002; Andersen et al. 2008).

Settling this question is important in order to rule out a number of suggested formation mechanisms for NCs. For example, if migration and/or merging of massive clusters is the dominant formation mechanism of NCs, as suggested by Bekki (2007), Capuzzo-Dolcetta & Miocchi (2008) and Agarwal & Milosavljevic (2011), one would expect to find a number of NCs displaced from the nucleus, as e.g. Georgiev et al. (2009) found for dwarf irregular galaxies.

Since not all late-type spirals harbour an obvious NC (Böker et al. 2002), one may also ask whether there is a galaxy property that prevents the formation of an NC. Nuclear star formation may be suppressed in galaxies with irregular gas kinematics, and hence there may be systematic differences in the gas rotation patterns of galaxies with and without NCs.

In order to address both these questions, we have obtained two-dimensional velocity fields of the ionized gas (as traced by the H\red{} line) for a sample of 20 late-type spiral galaxies. The use of H\red{} as a tracer for the general gas kinematics is required for an accurate comparison of the position of the kinematic centre (KC) and the PC, because it can be observed at high spatial resolution. While H\red{} may be affected by stellar winds, supernovae or other deviations from the pure disc rotation, in general, it has been found to represent well the overall rotation field of the neutral (i.e. H\i{} ) gas (Swaters et al. 2009).

Similar studies have been performed in the past (e.g. Ganda et al. 2006; Bershadly et al. 2010), but this study is the first to focus exclusively on bulgeless spirals. In addition, our analysis includes parametrized descriptions of the H\red{} rotation curve for all galaxies, thus enabling a direct comparison with the kinematics of other gas components.

This paper is structured as follows. Following this introduction, we describe in Section 2 the galaxy sample, the observations and data reduction methods. In Section 3, we detail the methods used to fit the H\red{} velocity fields, to derive the H\red{} rotation curves and to extract the location of the KC. We discuss our results in Section 4 and conclude in Section 5.

2 GALAXY SAMPLE AND OBSERVATIONS

2.1 Sample selection

The galaxy sample discussed here was selected from the sample of Böker et al. (2002) and thus consists of spirals with late Hubble type (Scd or later) and low inclination (<40°). In order to gauge the importance of an NC for the H\red{} kinematics, we selected galaxies with and without an NC in roughly equal parts. Given the visibility constraints from Calar Alto\(^1\) and WIYN\(^2\), we identified a sample of 20 objects, summarized in Table 1. The object distances are between 6 and 28 Mpc, which implies that the field of view (FOV) of the PPAK and SPARSEPAK instruments cover between 2 and 9.5 kpc in radius. The main instrumental parameters of PPAK and SPARSEPAK are summarized in Table 2.

2.2 PPAK data

During the nights of 2007 May 7 and 8, 13 galaxies of our sample were observed at the 3.5-m telescope of the Calar Alto observatory, using the Potsdam Multi-Aperture Spectrograph (Roth et al. 2005) in its PPAK mode (Kelz et al. 2006). The PPAK science fibre bundle consists of 382 fibres of 2.7-arcsec diameter each, of which 331 (the science fibres) are concentrated in a hexagonal bundle covering an FOV of 72 × 64 arcsec\(^2\) with a filling factor of \( \sim 65 \) per cent. The sky background is sampled by 36 additional fibres, distributed into six bundles of six fibres each, distributed along a circle of \( \sim 90 \) arcsec from the centre of the instrument FOV. The sky fibres are distributed among the science fibres within the pseudo-slit in order to have a good characterization of the sky; the remaining 15 fibres are used for calibration purposes. Cross-talk between adjacent fibres is estimated to be less than 5 per cent when using a simple aperture extraction (Sánchez 2006). Adjacent fibres in the pseudo-slit may cover very different locations on the sky, thus further reducing the effect of cross-talk.

The J1200 grating, mounted backwards in second order, was used for all observations. It covers the wavelength range of \( \sim 6350 - 6690 \) Å with a spectral resolution of full width at half-maximum (FWHM) of \( \sim 0.5 \) Å (\( R \sim 11 \) 000). For each galaxy, two exposures were taken, with exposure times between 900 and 1500 s, depending on the target brightness. The nights were clear, with a slightly elevated extinction (A\U{} \sim 0.18 mag), but stable in both cases. The seeing was variable, ranging between 0.8 and 1.3 arcsec. A spectrophotometric standard star was observed each night, in order to correct for the transmission curve of the instrument. Note though that spectrophotometric accuracy is not required for our analysis.

The data were reduced using r3m\(^3\) (Sánchez 2006), in combination with IRAF\(^4\) packages and r3d\(^3\) (Sánchez 2004). The reduction consists of the standard steps for fibre-based integral-field spectroscopy. A

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\(^1\) The German–Spanish Astronomical Center (CAHA) is jointly operated by the Max-Planck-Institut für Astronomie Heidelberg and the Instituto de Astrofísica de Andalucia (CSIC).

\(^2\) The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University and the National Optical Astronomy Observatories.

\(^3\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^4\) The reduction was performed using IRAF, which is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
master bias frame (created by averaging all bias frames observed during the night) was subtracted from the science frames. Exposures of a given sky position were median-combined using IRAF routines, thus clipping any cosmic rays. The locations of the spectra on the CCD were traced using an exposure of a continuum lamp taken before the science exposures. Each spectrum was then extracted from the science frames and stored in a row-stacked-spectrum file (Sánchez 2004). Wavelength calibration was performed using the position of Ne lines in lamp exposures obtained before and after each pointing, yielding an accuracy of rms ~0.15 Å. Differences in the relative fibre-to-fibre transmission throughput were corrected by comparing the wavelength-calibrated science frames with the corresponding frames derived from sky exposures taken during twilight. Then, the data were corrected for the average instrument throughput curve, by comparing the observed spectrum of the spectrophotometric calibration star with a flux-calibrated one. Finally, a contemporaneous (average) night sky spectrum was obtained by combining the spectra of the 36 sky fibres and subtracted from the science spectra. The relative location of the final science spectra on the sky was obtained via the standard PPAK position table.

### Table 2. Instrumental parameters.

<table>
<thead>
<tr>
<th>PPAK</th>
<th>SPARSEPAK</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of science fibres</td>
<td>331</td>
</tr>
<tr>
<td>No. of sky fibres</td>
<td>36</td>
</tr>
<tr>
<td>Size of fibres</td>
<td>2.7 arcsec</td>
</tr>
<tr>
<td>FOV</td>
<td>72 × 64 arcsec²</td>
</tr>
<tr>
<td>Filling factor</td>
<td>~57 per cent</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>6350–6690 Å</td>
</tr>
<tr>
<td>Instrumental FWHM</td>
<td>0.5 Å</td>
</tr>
</tbody>
</table>

#### 2.3 SPARSEPAK data

Nine galaxies in our sample were observed using SPARSEPAK (Bershady et al. 2004) on the 3.5-m WIYN telescope during the course of four nights, namely 2007 March 27–30.

SPARSEPAK is a fibre optic array that feeds light from the WIYN Nasmyth f/6.3 focus imaging port to the Bench Spectrograph. The SPARSEPAK integral field unit (IFU) consists of 82 fibres with a diameter of 4.675 arcsec each, arranged in a sparse grid with a field of regard of ~70 × 70 arcsec², thus offering good coverage and sampling of our target galaxies. The spectrograph was configured with the Bench Spectrograph Camera (BSC) and an Echelle grating with 316 lines mm⁻¹, used in eighth order. It covers the wavelength range 6500 Å < λ < 6900 Å with a dispersion of 0.195 Å pixel⁻¹ [8.6 (km s⁻¹) pixel⁻¹] and an instrumental FWHM of 0.67 Å (30.5 km s⁻¹).

This rather high resolution is mandatory for our purpose: fitting velocity field models to galaxies with observed rotation velocities of roughly 100 km s⁻¹ requires a centroiding accuracy of ~5 km s⁻¹. The BSC images the spectrograph on to a T2KA CCD with 2048 × 2048 pixels. The spectra are aligned along the columns of the CCD. The chip has a read noise of 4 e⁻ and was used with the standard gain of 2.1 e⁻/ADU. The system throughput for this set-up is roughly 4 per cent (Bershady et al. 2005).

The sparse grid can be filled in with three pointings, and we observed eight of the nine galaxies with three pointings (NGC 5789 was only observed with two pointings). When WIYN first points...
to a target, the slit-viewing camera is used to put the PC roughly coincident with fibre 52 at the centre of the SPARSEPAK array (if the target has a surface brightness that is too low, as is the case for many of these targets, we trust that the WIYN pointing is accurate enough to deliver the science target on to the fibre array after offsetting from a nearby star). After $2 \times 20$ min$^2$ exposures (we use two exposures to be able to better reject cosmic rays), guiding is stopped, and the telescope is offset by 5.6 arcsec towards the South and guiding is resumed. After the next $2 \times 20$ min$^2$ exposures, guiding is paused, and the telescope is offset by 4.9 arcsec west and 2.8 arcsec north from the second position. Guiding is resumed, and the final $2 \times 20$ min$^2$ exposures for a galaxy are taken.

Data were overcor- and bias-corrected and trimmed using the National Optical Astronomy Observatories IRAF package CCDPROC. Cosmic-ray rejection was performed before spectral extraction, using the method described in Andersen et al. (2006). Following cosmic-ray cleaning, basic spectral extraction, flattening and wavelength calibration were done using the IRAF package DOHYDRA. During this process, we made use of bias frames, dome flats and thorium argon emission spectra that were taken each night. Finally, the emission from the night sky was subtracted by averaging the spectra of the seven sky fibres and subtracting the result from each of the 75 source spectra.

2.4 Image registration

In order to correlate the results of the kinematical analysis with the galaxy morphology, and in particular the positions of KC, PC and NC, we use archival Hubble Space Telescope (HST)/Wide Field Planetary Camera 2 (WFPC2) F814W images (roughly corresponding to the Johnson I band) from the snapshot survey of Böker et al. (2002). For each galaxy, we first created a continuum image from the IFU data cube by fitting the continuum in a spectral window free of emission lines. This should allow a fair comparison to the I-band images. We then smoothed the HST image with a Gaussian beam whose width matches the seeing-limited resolution of the IFU observations (typically 1.0 arcsec).

We cross-correlated both images as follows: for a given position of the (smoothed) HST image, we extracted its flux within the footprint of each IFU spaxel. We then fitted a linear relation between the IFU and the HST spaxel fluxes and tabulated $\chi^2$. We repeated this process over a grid of offsets between both images, thus ‘mapping’ $\chi^2$. The offset grid has a granularity corresponding to five times the pixel size of the WFPC2 data, i.e. 0.232 arcsec. The location of the $\chi^2$ minimum within the offset grid was used as the best registration and the minimum $\chi^2$ value to estimate the uncertainty in the registration (see Fig. 1 for an illustration).

2.5 Line fitting and extraction of velocity fields

Once spectra were processed as described in Section 2, we identified Hz emission lines and measured fluxes, widths, centres and the corresponding errors for lines in a given spectral window. We detected Hz emission lines and measured their fluxes, widths and centroids in 3078 of 4303 PPAK and 1220 of 1950 SPARSEPAK object spectra (72 and 63 per cent detection rate, respectively). While the galaxy described in Andersen et al. (2008), NGC 2139, contained multiple kinematic components in each spectra, most emission lines in this sample were best fitted by a single Gaussian line. Furthermore, typically 10 spectra per galaxy were best fitted by two Gaussians with centres that were close to being coincident, i.e. the lines appeared to have a strong core with broader, low-level wings. Still, the centre positions and widths of these lines can be very well fitted by a single Gaussian (see Fig. 2). Only about two to three lines per galaxy exhibited two decoupled Gaussian profiles. Almost all of these double-line features occur at the very centre of the galaxies. In the case of double-line features, we used the more highly peaked, dominant component of the line fit to derive the velocity map.

3 ANALYSIS

3.1 Kinematic modelling

In order to interpret the Hz velocity fields that result from the analysis described in the last section, we fit them with a kinematic model. While there are arguments for fitting a more flexible tilted ring model, which allows for warps in the gas discs, the sometimes sparse sampling of the overall velocity field of our data did not allow this approach for all galaxies. In the interest of a uniform analysis for the entire sample, we therefore chose to follow the approach of Courteau (1997) who proposed the following parametric form for the (deprojected) rotation curve:

$$v(r) = v_0 + \frac{2}{r} v_\text{e} \arctan \left( \frac{r - r_0}{r_\text{i}} \right).$$

(1)

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Ha kinematics of bulgeless discs

The kinematic parameters as derived in this paper are (2) systemic velocity, (4) position to the major axis, (5) inclination, (6) and (7) RA and Dec. of the KC, (8) error on the KC, (9) circular velocity, defined as the maximum velocity in the rotation curve fits, and (10) the scale radius of the rotation curve. For comparison to the modelled systemic velocity (2), we give the systemic velocity assembled through NED (3).

### Table 3. Final kinematic parameters.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$V_{\text{sys}}$</th>
<th>$V_{\text{sys,NED}}$</th>
<th>PA</th>
<th>$i$</th>
<th>Centre RA (hh:mm:ss.ss)</th>
<th>Centre Dec. (dd:mm:ss.s)</th>
<th>Centre error (arcsec)</th>
<th>$v_{\text{circ}}$ (km s$^{-1}$)</th>
<th>$r_i$ arcsec</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3574$^2$</td>
<td>1438 ± 2</td>
<td>1441</td>
<td>98.4</td>
<td>25.3</td>
<td>06:53:10.43</td>
<td>+57:10:37.9</td>
<td>0.9</td>
<td>167.2 ± 0.3</td>
<td>198.4 ± 0.4</td>
</tr>
<tr>
<td>NGC 2552$^2$</td>
<td>511 ± 3</td>
<td>524</td>
<td>62.4</td>
<td>25.4</td>
<td>08:19:19.44</td>
<td>+50:00:48.7</td>
<td>2.3</td>
<td>62.2 ± 1.6</td>
<td>221.0 ± 1.9</td>
</tr>
<tr>
<td>NGC 4499$^2$</td>
<td>685 ± 2</td>
<td>691</td>
<td>141.9</td>
<td>29.0</td>
<td>08:37:41.49</td>
<td>+51:39:13.6</td>
<td>6.8</td>
<td>50.9 ± 1.6</td>
<td>200.2 ± 2.7</td>
</tr>
<tr>
<td>NGC 5283$^1$</td>
<td>576 ± 5</td>
<td>556</td>
<td>56.7</td>
<td>29.9</td>
<td>09:51:16.88</td>
<td>+07:49:47.3</td>
<td>4.3</td>
<td>48.6 ± 0.4</td>
<td>179.0 ± 0.4</td>
</tr>
<tr>
<td>NGC 3206$^2$</td>
<td>1151 ± 1</td>
<td>1150</td>
<td>183.0</td>
<td>26.5</td>
<td>10:21:47.81</td>
<td>+56:55:49.8</td>
<td>0.6</td>
<td>78.4 ± 0.1</td>
<td>229.3 ± 1.2</td>
</tr>
<tr>
<td>NGC 3346$^1$</td>
<td>1274 ± 1</td>
<td>1260</td>
<td>−67.1</td>
<td>29.4</td>
<td>10:43:38.85</td>
<td>+14:52:16.6</td>
<td>0.6</td>
<td>123.6 ± 0.8</td>
<td>207.1 ± 1.3</td>
</tr>
<tr>
<td>NGC 3423$^2$</td>
<td>1004 ± 2</td>
<td>1011</td>
<td>45.1</td>
<td>19.0</td>
<td>10:51:14.36</td>
<td>+05:50:24.3</td>
<td>1.1</td>
<td>127.0 ± 0.5</td>
<td>295.6 ± 1.2</td>
</tr>
<tr>
<td>NGC 3445$^1$</td>
<td>2048 ± 1</td>
<td>2069</td>
<td>−9.8</td>
<td>27.6</td>
<td>10:54:35.21</td>
<td>+56:59:23.7</td>
<td>1.9</td>
<td>148.1 ± 2.3</td>
<td>132.1 ± 4.9</td>
</tr>
<tr>
<td>NGC 4204$^1$</td>
<td>870 ± 3</td>
<td>856</td>
<td>240.2</td>
<td>13.6</td>
<td>12:15:14.36</td>
<td>+20:39:29.6</td>
<td>5.0</td>
<td>23.8 ± 0.8</td>
<td>238.0 ± 19.3</td>
</tr>
<tr>
<td>NGC 4299$^1$</td>
<td>237 ± 2</td>
<td>232</td>
<td>−110.3</td>
<td>28.7</td>
<td>12:21:40.59</td>
<td>+11:30:11.4</td>
<td>0.9</td>
<td>109.1 ± 1.1</td>
<td>189.9 ± 4.8</td>
</tr>
<tr>
<td>NGC 4496$^1$</td>
<td>1747 ± 3</td>
<td>1730</td>
<td>47.5</td>
<td>30.4</td>
<td>12:31:39.75</td>
<td>+03:56:18.9</td>
<td>1.7</td>
<td>94.3 ± 0.2</td>
<td>221.3 ± 0.5</td>
</tr>
<tr>
<td>NGC 4517$^1$</td>
<td>1522 ± 3</td>
<td>1509</td>
<td>−156.6</td>
<td>33.7</td>
<td>12:32:28.32</td>
<td>+00:23:28.7</td>
<td>1.9</td>
<td>68.6 ± 0.8</td>
<td>175.5 ± 3.8</td>
</tr>
<tr>
<td>NGC 4540$^2$</td>
<td>1291 ± 2</td>
<td>1286</td>
<td>13.9</td>
<td>27.9</td>
<td>12:34:50.91</td>
<td>+15:33:06.3</td>
<td>1.4</td>
<td>83.4 ± 1.5</td>
<td>201.0 ± 2.6</td>
</tr>
<tr>
<td>NGC 4625$^2$</td>
<td>621 ± 1</td>
<td>609</td>
<td>−55.8</td>
<td>13.3</td>
<td>12:41:53.06</td>
<td>+41:16:24.0</td>
<td>1.3</td>
<td>38.7 ± 0.2</td>
<td>188.3 ± 1.3</td>
</tr>
<tr>
<td>NGC 4904$^2$</td>
<td>1180 ± 1</td>
<td>1189</td>
<td>−134.0</td>
<td>38.5</td>
<td>13:00:58.62</td>
<td>−00:01:37.8</td>
<td>0.3</td>
<td>105.2 ± 0.2</td>
<td>235.1 ± 1.8</td>
</tr>
<tr>
<td>NGC 4904$^2$</td>
<td>1162 ± 2</td>
<td>1189</td>
<td>227.2</td>
<td>39.0</td>
<td>13:00:58.54</td>
<td>−00:01:37.9</td>
<td>0.4</td>
<td>105.2 ± 0.9</td>
<td>247.5 ± 2.8</td>
</tr>
<tr>
<td>NGC 8516$^1$</td>
<td>1026 ± 3</td>
<td>1023</td>
<td>14.5</td>
<td>43.3</td>
<td>13:31:52.60</td>
<td>+20:00:03.9</td>
<td>1.4</td>
<td>60.2 ± 0.9</td>
<td>154.5 ± 1.2</td>
</tr>
<tr>
<td>NGC 5669$^2$</td>
<td>1368 ± 2</td>
<td>1371</td>
<td>69.1</td>
<td>35.6</td>
<td>14:32:44.06</td>
<td>+09:53:29.5</td>
<td>0.5</td>
<td>98.4 ± 0.5</td>
<td>186.6 ± 0.6</td>
</tr>
<tr>
<td>NGC 5789$^1$</td>
<td>1811 ± 1</td>
<td>1805</td>
<td>150.3</td>
<td>27.4</td>
<td>14:56:35.58</td>
<td>+30:14:02.4</td>
<td>1.2</td>
<td>122.9 ± 1.0</td>
<td>140.3 ± 6.0</td>
</tr>
<tr>
<td>NGC 5789$^2$</td>
<td>1809 ± 2</td>
<td>1805</td>
<td>151.7</td>
<td>27.0</td>
<td>14:56:35.56</td>
<td>+30:14:01.1</td>
<td>2.2</td>
<td>129.2 ± 1.3</td>
<td>148.8 ± 4.5</td>
</tr>
<tr>
<td>NGC 5964$^1$</td>
<td>1457 ± 4</td>
<td>1447</td>
<td>131.8</td>
<td>38.4</td>
<td>15:37:36.94</td>
<td>+05:58:17.3</td>
<td>5.1</td>
<td>120.8 ± 0.8</td>
<td>220.1 ± 1.2</td>
</tr>
<tr>
<td>NGC 6509$^1$</td>
<td>1780 ± 1</td>
<td>1813</td>
<td>−81.6</td>
<td>49.3</td>
<td>17:59:25.46</td>
<td>+06:17:10.5</td>
<td>0.3</td>
<td>218.1 ± 0.4</td>
<td>213.7 ± 0.7</td>
</tr>
</tbody>
</table>

Note: Galaxies marked with superscript 1 were observed with CAHA/PPAK and those marked with superscript 2 were observed with WIYN/SPARSEPAK. The kinematic parameters as derived in this paper are (2) systemic velocity, (4) position to the major axis, (5) inclination, (6) and (7) RA and Dec. of the KC, (8) error on the KC, (9) circular velocity, defined as the maximum velocity in the rotation curve fits, and (10) the scale radius of the rotation curve. For comparison to the modelled systemic velocity (2), we give the systemic velocity assembled through NED (3).

References:

- Kamphuis & Sancisi 1993
- Andersen et al. 2006
- Sellwood & Sánchez 2010
- Courteau 1997
3.2 Uncertainties in the kinematic modelling

For an independent check, we compared our results to the apparent maximal rotation velocity of the gas (parameter \( v_{\text{max}} \)) from the HyperLeda data base\(^4\) (Paturel et al. 2003). As pointed out by Courteau (1997), the parameter \( v_c \) in equation (1) is in itself not a good measure of the maximal velocity. Instead, we use \( v_{\text{max}} \), i.e. the model velocity at three times \( r_c \). Fig. 3 shows that \( v_{\text{max}} \) correlates well with the \( v_{\text{max}} \) parameter from LEDA, after correction for the galaxy inclination as derived from our fits. There are a number of uncertainties underlying the plotted values giving rise to the scatter in the plotted relation, such as irregularities in the velocity fields for both H\(\alpha\) and H\(\alpha\) or the fact that we do not sample the full velocity field with our H\(\alpha\) data. Given these uncertainties, the scatter is surprisingly low. This demonstrates the reliability of our kinematic models.\(^5\)

A further consistency check can be performed by comparing the dynamical models derived from PPAK and SPARSEPAK data for NGC 4904 and 5789, the two galaxies which have been observed with both instruments. As can be seen from Fig. 4, the observations agree well in both cases. The fit results also agree well, both in the location of the KC and in the overall shape of the \( \chi^2 \) contours, despite marked differences in the spatial sampling. We take this as confirmation of both the quality of our data and the robustness of our analysis method.

\(^4\) http://leda.univ-lyon1.fr

\(^5\) We note that it is doubtful whether further exploration of our data for the Tully–Fisher relation purposes is reasonable, due to the many kinematic uncertainties we identify.

However, our main uncertainty in the velocity field modelling is the actual complexity of the velocity fields. Our simple model does e.g. not include the effects of streaming motions due to bars or the effects on the velocity field due to interactions with a companion...
Figure 4. Montage of the sample galaxies sorted by right ascension, one line per galaxy. Panels from left to right: (i) SDSS r-band (when available) or DSS R-band image, with two footprints per galaxy overplotted. The small square footprint indicates the HST WFPC2 FOV, the larger square gives the SPARSEPAK and the hexagon the PPAK footprint. (ii) Hα flux map and (iii) observed Hα velocity map in comparison to (iv) the modelled velocity field (masked with the observed flux map). The right-hand panels show the HST WFPC2 F814W image with a transparent overlay of the velocity map. Gaps in the velocity map are filled in with model values. The white cross indicates the position and uncertainty of the PC (as derived by Böker et al. 2002); black contours indicate the position and uncertainty of the KC (from 1σ to 6σ, marginalized over all other parameters), derived in this paper.

galaxy. We have performed an eye-ball check of our trust in the velocity field modelling, by looking at the spacing of the $\chi^2$ contours of the fit to the dynamical centre (see Fig. 4, Column 5), weighing in the presence/absence of a bar/companion, the filling factor of Hα emission, the overall regularity of the velocity field and the quality of the fit to the rotation curve. On this basis, we have assigned quality flags from 0 (unusable) over 1 (low trust) to 2 (well modelled) to each velocity field. This quality assessment number is added as a column in Table 4. This exercise has been somewhat sobering as to our ability to systematically determine dynamical galaxy centres, as only seven velocity fields out of 22 obtain the label ‘well modelled’. Only two of these are neither barred nor show any other sign of problems (NGC 3423 and 3206). Late-type disc galaxies tend to be irregular, and a well-defined centre simply does not exist in quite a
few of them. The implications of this will be further discussed in Section 4.

3.3 Comparing kinematic centres and photocentres

Following image registration as described in Section 2.4, we can measure the absolute coordinates of the best-fitting KC. Table 4 summarizes the KC positions, along with those of the PC and NC (if present). The latter two were derived from isophotal fits to the WFPC2 image, as described in Böker et al. (2002). All coordinates in Table 4 refer to the J2000 coordinate system of the HST image, which has an absolute accuracy with respect to the International Celestial Reference System of ~1 arcsec. In Fig. 5, we compare the relative positions of the NC and the KC as well as the PC and the KC for the non-nucleated galaxies.

Generally, we find that there are only a few galaxies (six out of 20) with a velocity field regular enough (trust level 2 in Table 4) to meaningfully compare the locations of NC, PC and KC. For all of these galaxies these locations agree within the uncertainties, although some of the galaxies show bars. On the other hand, for all but one galaxy with offset KC we can always identify a reason. NGC 2552, 4299 and 5789 have a very fuzzy or patchy appearance...
in Hα and in stellar emission. These galaxies may simply not be in regular rotation. UGC 5288, NGC 4204, 4496, 5669, 5964 and 6509 show a strong bar and the velocity field is clearly affected by large-scale streaming motions along the bar. NGC 4625 is lopsided from a strong $m = 1$ mode, which seems to displace the KC. There are only two potentially odd cases: in NGC 4517 there is a large offset between KC and NC. However, this galaxy probably has a nuclear starburst (see the Hα map) that affects the central part of the velocity field, although a possible bar is weak if existent. UGC 3574 looks very regular, yet NC and KC show an offset of the size of the 1σ error bar. However, in this galaxy the central 5 arcsec unfortunately do not show Hα emission, which might hamper our ability to determine an accurate KC. We are left with no confirmed offset between the NC and the KC.

3.4 Rotation curves and velocity residuals

Rotation curves of our sample galaxies are shown in Fig. 6. As mentioned in Section 3.1, we find that the functional form given in equation (1) represents the rotation curves of latest type spirals well in general. To quantify this statement in terms of the scientific goal of our paper, we have used the rotation curves of our best models
Figure 4 – continued

(trust level 2 in Table 4) and our bad models (trust level 0). There is no obvious trend with nucleatedness (four out of six well-fitted galaxies are nucleated and one out of three not well-fitted galaxies).

Those rotation curves which are least consistent with the arctan functional form are dominated by irregularities of their host galaxies. The irregular rotation curve of NGC 4625 can be explained by an ongoing interaction, while NGC 5964 is strongly barred and UGC 4499 has a very sparsely sampled velocity field.

The rotation curve shapes of late-type galaxies have also been discussed in Swaters et al. (2009) from H I data. The morphological variety of their rotation curves is similar to ours.

3.5 Dynamical friction time-scales

Based on Chandrasekhar’s formula, we calculate the dynamical friction time-scales for star clusters in our galaxies using equation (8.12) of Binney & Tremaine (2008):

$$t_{	ext{fric}} = \frac{1.17 r_i^2 v_c}{\ln \Lambda G M}$$

where $\ln \Lambda$ is the Coulomb logarithm, $v_c$ is the typical velocity of the stars in the galaxy at radius $r_i$ and $M$ is the mass of the test particle that is going through the much larger mass of the underlying galaxy. Although Binney & Tremaine (2008) derived equation (2)
for the decay of black hole orbits in a singular isothermal sphere, they explicitly state that it is approximately correct even for mass distributions other than the singular isothermal sphere (given that the mass ratio of the subject body to the interior mass of the host \( \ll 1 \)). For point-like particles, \( \Lambda \approx \frac{v_i^2}{v_c^2} \gg 1 \), while for extended bodies the Coulomb logarithm is obtained from \( N \)-body simulations, which give values of \( \ln \Lambda \sim 2–7 \) (Spinnato, Fellhauer & Portegies Zwart 2003; Peñarrubia et al. 2004). The calculation of \( t_{\text{fric}} \) requires the typical stellar velocity, while we are actually measuring the velocity fields of the ionized gas. The circular velocity of the stars in the central region of disc galaxies will be 1.5–2 times slower than the ionized gas (Ganda et al. 2006) due to asymmetric drift. We scale our measured velocity values to take that into account.

We calculate the dynamical friction time-scale for clusters (taken to be point-like test particles) of masses between \( 10^4 \) and \( 10^7 \) \( M_\odot \), which start at an initial distance of \( \sim 500 \) pc to the centre. We find that typically clusters with masses above \( 2 \times 10^5 \) \( M_\odot \) will make it to the dynamical centre within \( \leq 2 \times 10^9 \) yr (see Fig. 7). These findings are in very good agreement with the recent study by Bekki (2010), who performed numerical simulations on dynamical evolution of disc galaxies and investigated the orbital evolution of star clusters influenced by dynamical friction against disc field.

Figure 5. Left: projected position of all NCs, relative to the KCs of their respective host galaxy. The size of the crosses denotes the 1σ error bar in the KCs. Right: offset of the PC relative to the KC of the non-nucleated galaxies. Here, the size of the crosses denotes the combined 1σ error in the KCs plus PCs. The colours of the symbols indicate how well the velocity fields can be modelled. Black symbols indicate a model with high fidelity, blue symbols denote models with low trust and red symbols denote galaxies that cannot be well modelled due to interactions or non-circular motions (see the text for details).
Bekki (2010) found that dynamical friction of star clusters against disc field stars is much more effective in orbital decay of star clusters in comparison with that against galactic haloes in disc galaxies. Moreover, dynamical friction seems to be most effective in discs with disc masses lower than $10^9 M_\odot$ owing to smaller stellar velocity dispersions. Milosavljević (2004) argued that dynamical friction time-scales are too long to bring massive clusters to the centres of late-type spiral galaxies. However, recently Agarwal & Milosavljević (2011) pointed out that Milosavljević (2004) only considered migration from a distant location in the disc, and indeed clusters that form close to the galactic centre can reach the centre and merge with the NC.

4 DISCUSSION

The main goal of this paper is to verify whether the NC and the KC in late-type, bulgeless galaxies always coincide and whether the presence or mass of an NC is related to the kinematic state of its host galaxy. As discussed in Section 3, we indeed find that for galaxies with high fidelity velocity fields, the NC, the KC and the PC coincide within the errors. A similar result was obtained by Trachternach et al. (2008) who concluded, based on H\textsc{i} rotation curves, that there are no systematic offsets between optical and KCs.

However, Trachternach et al. (2008) also concluded that, based on H\textsc{i} observations, non-circular motions are small, especially in
late Hubble types. As has become evident, this is not the case for velocity fields with higher spatial resolution and derived from the ionized gas.

Our derived velocity fields compare well with the literature results. For example, Ganda et al. (2006) have published H$\beta$ velocity fields for NGC 3346 and 3423. While they did not perform kinematic modelling of their data, i.e. did not publish rotation curves or the KC location, the general shape and orientation of their velocity fields agree well with those published here.

Two of our galaxies, NGC 5964 and 6509, are also part of the recent H I study of bulgeless spirals by Watson et al. (2010). Comparing our H$\alpha$ velocity fields to their H I data, we find that the position angles and velocity scales are in good agreement between atomic and ionized hydrogen. The advantage of the H I maps is their large FOV, which covers the entire galaxy and thus the complete rotation curve. Our H$\alpha$ velocity fields cover a good fraction of the rotation curves, but for some galaxies we are restricted to the central part of the velocity gradient and do miss the turnover of the velocity curve, like in the case of NGC 5964. This results in large error bars on the location of the KC. We compare the KC position derived from H I (Watson et al. 2010) and H$\alpha$ and find good agreement in the case of NGC 6509, but for NGC 5964 the offset is larger than the measurement error. This is reflected in the fact that the best fit to the velocity field of NGC 5964 appears unreliable.

We have used our measurements to derive realistic dynamical friction time-scales for all sample galaxies (see Section 3.5). We find that the threshold mass for a star cluster to be able to migrate to the centre efficiently from a realistic distance ($\sim$500 pc) is $1-2 \times 10^5 M_\odot$ [in very good agreement with the numerical simulations by Bekki (2010)]. This is indeed the observed lower mass threshold for NCs. Böker et al. (2002) found that there is a lower luminosity cut-off to the NC luminosity function at $M_I = -9$. For a known mass-to-light ratio (M/L), this would imply a lower limit mass cut-off for NCs. Walcher et al. (2005) published dynamically determined M/L for a sample of nine NCs with a mean of $M/L_\alpha = 0.6$. This would translate into an observed lower mass limit for NCs of $\approx 10^5 M_\odot$.

We thus find that our data are entirely consistent with an NC formation scenario in which a massive seed cluster forms within $\sim$500 pc from the centre of the galaxy and spirals in to the centre due to dynamical friction. This scenario has the advantage of automatically accounting for galaxies without a nuclear star cluster, implying merely that no suitable seed clusters formed close enough to the centre in these discs. We also note that this lower mass threshold is one order of magnitude lower than the threshold mass of $\approx 10^6 M_\odot$ derived by Pfenniger-Alenburg & Kroupa (2009) for efficient accretion of gas into the NC, which would lead to repetitive bursts of star formation there. Therefore, it may be that further NC growth through in situ star formation starts out quite slowly, but picks up in pace as the NC grows. Mass growth may be further supported by accretion of other massive inspiralling clusters. Soon after its formation the seed cluster would then satisfy our definition and observations of a nuclear star cluster, namely being massive, sitting close to the centre, having undergone recurrent star formation and being compact. This formation and growth mechanism is also supported by the fact that NCs are observed to rotate (Seth et al. 2008; Seth et al. 2010).

The long dynamical friction time-scales we infer for massive star clusters that are initially located at significant (>1 kpc) distances from the galaxy centre do not favour models where the NC grows only through accretion of globular clusters. We emphasize on the other hand that we have not found a confirmed case where the NC sits outside of the KC. We thus cannot rule out in situ formation scenarios for NCs from our data.

### 5 CONCLUSIONS

We have presented two-dimensional H$\alpha$ velocity fields for 20 late-type, disc-dominated spiral galaxies, the largest sample of bulgeless discs with high-resolution H$\alpha$ velocity fields to date.

We fitted the data with kinematic models in order to derive rotation curves and the location of the dynamical centres. Most rotation curves are well fitted by the arctan form of Courteau (1997) used for earlier type spirals. We find that the velocity fields span a broad range of morphologies. Some galaxies show regular rotation, which allows accurate determination of the KC. However, only two out of 20 galaxies have a completely regular velocity field. Many galaxies without bulges, but with strong bars show steep rises of their ‘velocity gradients’ (‘rotation curves’) in the inner part. These steep rises are not necessarily due to mass concentrations, but to streaming motions along the bar. However, quite a few have some degree of irregular gas motion, which in nearly all cases either can be attributed to the presence of a bar or is connected to a rather patchy appearance of the H$\alpha$ emission and the stellar light. Thus, most galaxies in the sample show strong gas motions that cannot be attributed to the overall gravitational potential of the...
galaxy, implying low surface mass densities (compare Dalcanton & Stilp 2010) and that many bulgeless galaxies are not in dynamical equilibrium.

There appears to be no systematic difference in the kinematics of nucleated and non-nucleated discs. For galaxies with regular, well-sampled velocity fields, the PC, the NC and the KC coincide within the errors. These centres also coincide for quite a few of the not-so-regular galaxies (in total, for 13 out of our sample of 20 galaxies). However, we also find that NCs also occur in galaxies with disordered rotation fields. Hence, the large-scale velocity field is not a good predictor for the presence or mass of an NC. Many formation scenarios for NCs invoke off-centre cluster formation and subsequent ‘sinking’ of clusters due to dynamical friction. We confirm that this scenario is viable for clusters that form within ~500 pc of the centre of the galaxy, as the dynamical friction time-scales inferred from our data are consistent with this scenario. More distant globular clusters do not seem to be promising candidates for NC seeds, due to their long dynamical friction time-scales. On the other hand, we point out that we cannot rule out an in situ formation scenario.

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REFERENCES


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