Bar pattern speed and position of the circumnuclear ring in NGC 1097

N. Piñol-Ferrer,1,2* K. Fathi,1,2 C. Carignan,3,4 J. Font,5 O. Hernandez,4 R. Karlsson1 and G. van de Ven6

1Stockholm Observatory, Department of Astronomy, Stockholm University, AlbaNova Centre, SE-106 91 Stockholm, Sweden
2Oskar Klein Centre for Cosmoparticle Physics, Stockholm University, SE-106 91 Stockholm, Sweden
3Department of Astronomy, University of Cape Town, Private Bag X3, Ronderbosch 7701, South Africa
4Département de physique, Université de Montréal C.P. 6128, succ. Centre-Ville, Montréal H3C 3J7, Canada
5Instituto de Astrofísica de Canarias, c/Vía Láctea, s/n, E-38 205 La Laguna, Spain
6Max Planck Institute for Astronomy, Königstuhl 17, D-69117, Heidelberg, Germany

Accepted 2013 November 5. Received 2013 October 20; in original form 2013 February 16

ABSTRACT
We present the first galactic-scale model of the gas dynamics of the prototype barred Seyfert 1 galaxy NGC 1097. We use large-scale FaNTOmM Fabry-Perot interferometric data covering the entire galactic disc and combine the distribution and kinematics maps with high-resolution two-dimensional spectroscopy from the Gemini telescope. We build a dynamical model for the gravitational potential by applying the analytic solution to the equations of motion, within the epicyclic approximation. Our model reproduces all the significant kinematic and structural signatures of this galaxy. We find that the primary bar is 7.9 ± 0.6 kpc long and has a pattern speed of 36 ± 2 km s⁻¹ kpc⁻¹. This places the corotation radius at 8.6 ± 0.5 kpc, the outer Lindblad resonance at 14.9 ± 0.9 kpc and two inner Lindblad resonances at 60 ± 5 pc and 2.9 ± 0.1 kpc. These derivations lead to a ratio of the corotation radius over bar length of 1.0−1.2, which is in agreement with the predictions of simulations for fast galaxy bars. Our model presents evidence that the circumnuclear ring in this galaxy is not located near any of the resonance radii in this galaxy. The ring might have once formed at the outer inner Lindblad resonance radius, and it has been migrating inwards, towards the centre of the galactic gravitational potential.

Key words: galaxies: active – galaxies: evolution – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION
The detailed understanding of a galaxy’s gravitational potential is imperative for setting a realistic and physical scenario for its formation and evolution. The gravitational potential is the sole actor in driving the initial gravitational collapse during a galaxy’s formation phase followed by possible follow-up interactions and mergers with neighbouring galaxies. Moreover, the evolution of structures in any galaxy is primarily governed by the strength and shape of its gravitational potential. Environmental effects may create evolution of structures by means of gravitational interactions, though, when structures evolve according to secular evolution scenarios, it is primarily governed by the strength and shape of the galactic gravitational potential.

One galaxy that has proven to be of particular importance for studying a wide range of gravitational effects is the nearby Seyfert 1 barred spiral galaxy NGC 1097, see Table 1. This galaxy is interesting since it displays the presence of a number of morphological and kinematic features, that are all interlinked by its gravitational field. At ~1 kpc, an almost circular ring-like feature marks a remarkable transition between the prominent R ~ 8 kpc galactic bar and the smooth region interior to the circumnuclear ring (Sersic 1958), placed at the turnover radius of the rotational curve (Wolstencroft & Schempp 1979). The bar hosts two prominent dust lanes, both originated at the outer edges of the bar, that cut the inner ring, where nuclear spiral arms continue down to ~3 pc distance from the active nucleus (Fathi et al. 2006), probably being the continuation of the large-scale dust lanes.

While these overall features make this galaxy interesting for the studies of the evolution of structures in barred spiral galaxies, the discovery of broad (~10 000 km s⁻¹) double-peaked Hα emission lines by Storchi-Bergmann, Baldwin & Wilson (1993) also makes NGC 1097 an ideal laboratory for studying the ‘fate’ of the gas accumulated in the centres of active galaxies (e.g. Storchi-Bergmann et al. 2003). NGC 1097 is thus most suitable for studying the processes that cause the material/fuel to lose its angular momentum and fall from the outer galactic edge towards the galactic centre. In rotating systems, perturbations can cause the potential to become non-axisymmetric, and torques exerted by the subsequent non-axisymmetric features are able to drive material towards the...
Table 1. Physical parameters adopted throughout this work.

| Parameter       | Value            |
|-----------------|------------------|
| NGC 1097        |                  |
| Coordinates     | RA: 02:46:19 Dec.: -30:16:30 |
| Morphology      | SB(s)b           |
| Type            | Seyfert 1        |
| Distance        | 14.5 Mpc         |
| P.A.            | 126–131°         |
| Inclination     | 35°              |
| Bar radius      | 107 arcsec       |

a Tully (1988).
Wolstencroft & Schempp (1979); Fathi et al. (2006); Davies et al. (2007); Hicks et al. (2009); van de Ven & Fathi (2010).
Fathi et al. (2006).
Erwin (2004).

centre of their host galaxy (e.g. Schwarz 1984; Shlosman, Frank & Begelman 1989). However, some authors as Hummel et al. (1990), Combes (2001) or García-Burillo et al. (2005) suggested that, although it is straightforward to transport gas down to the central few hundreds of parsec and induce enhanced star formation, it is more difficult to make the gas reach smaller scales required to fuel an active galactic nucleus (AGN).

The somewhat enhanced frequency of nuclear spirals at the centre of active galaxies as compared to non-active galaxies (e.g. Martini et al. 2003) supports the hypothesis that nuclear spirals may aid in finalizing the last leg of the journey of the gas on to an AGN. In NGC 1097, nuclear spirals were found in images by Lou et al. (2001), and kinematically confirmed by Fathi et al. (2006). Later, van de Ven & Fathi (2010), Davies et al. (2009) and Piñol-Ferrer et al. (2011) measured the inflow rates of multiple phases of the interstellar medium along the nuclear spiral arms. However, none of these studies have appropriately accounted for the galactic-scale gravitational potential, simply due to the lack of observational data, which makes impossible to completely understand the nature of these spiral arms in NGC 1097.

Notwithstanding, it is imperative that one builds a global and realistic model for the overall galactic-scale gravitational potential in order to explore the physical processes responsible for the nuclear spirals and that act on the mass transfer along them. Such model has been missing to date.

Here, we present the global dynamical model of NGC 1097, based on a comprehensive set of high-resolution imaging and kinematic data across the face of the galaxy. The model is based on the analytic solution of the equations of motion within the epicyclic approximation, in which we introduce a gravitational potential derived from a two-dimensional ionized gas velocity field and an infrared image. Our model simultaneously accounts for the galactic bar and spiral arms, and we have introduced a damping coefficient for adequate appearance of the resonance radii in such a way that the model can reproduce the data. The analytic solution of the equations of motion describes the response of interstellar matter, originally in circular orbits, to the gravitational potential. These solutions can be computed in few seconds, making this methodology/technique very efficient to study the large parameter space involved.

2 DATA

The dynamical model presented here is based on two-dimensional kinematic measurements of the Hα, [N II] and H i data.

The Hα kinematics and distribution are products of the FaNTomM Fabry-Perot interferometric observations at the 3.6 m telescope from the European Southern Observatory, La Silla, Chile. Instrument specifications can be found in Hernandez et al. (2003), and a preliminary presentation of the NGC 1097 data can be found in Dicaire et al. (2008). The Fabry-Perot data are a mosaic that cover the whole galaxy, with a spatial resolution of 1.9 arcsec and the spectral resolution 15 km s⁻¹ (see Fig. 1, right-hand panel).

Figure 1. Left: composite three-colour image of NGC 1097 taken with the VIMOS instrument on the 8.2-m Melipal (Unit Telescope 3) of ESO’s Very Large Telescope (Credit: ESO/Gendler) with the contour map of the FaNTomM Fabry-Perot observations. Pixels with signal-to-noise ratio larger than 5 are highlighted. Right: Hα velocity field at a spatial sampling of 0.83 arcsec, taken with FaNTomM on the ESO La Silla 3.6 m. In both panels, north is up and east is left. The GMOS-IFU data used throughout this paper cover a region interior to the central star-forming ring.
To get a more detailed view of the central kpc, we use two-dimensional Hα and [N ii] velocity fields, with 0.3 arcsec spatial resolution and 85 km s⁻¹ spectral resolution, obtained with the Gemini South Telescope’s Integral Field Unit (GMOS-IFU). The data and all corresponding quality and reduction specifications can be found in Fathi et al. (2006). The velocity information of both lines is almost identical with equal rotation curves, with the only difference that the Hα velocity field appears slightly noisier. For illustration purposes, when presenting the central velocity field, we will therefore display the [N ii] velocity field throughout this paper.

In order to compare the kinematics in the outer parts of the galaxy, we use the H i velocity field presented by Higdon & Wallin (2003). This velocity field was observed with Very Large Array in the hybrid DnC configuration, with a channel separation of 20.7 km s⁻¹ and a synthesized beam FWHM of 56 arcsec.

Finally, to probe the overall galactic potential, we further use imaging data from the old stellar population based on the 3.6 µm image from the Spitzer telescope (Kennicutt et al. 2003). The Spitzer observations cover the galaxy with a spatial resolution of 1.7 arcsec.

3 A DYNAMIC MODEL FOR NGC 1097

To build a dynamical model for the gravitational potential of NGC 1097, we apply the analytic solution within the epicyclic approximation. The analytic model we used was first developed by Sanders & Huntley (1976), and then by Lindblad & Lindblad (1994) and Wada (1994) who included a special analysis on the resonant radii. This analysis was used to fit observations by Lindblad, Lindblad & Athanassoula (1999, hereafter LLA99), Sakamoto et al. (1999), Baker (2000) or Boone et al. (2000), but assuming always a barred gravitational potential. For NGC 1097, we generalize this analytic model for an arbitrary galaxy potential.

Hence, we introduce the arbitrary gravitational potential in the analytic study and adjust the appearance of the resonances by using damping coefficients. The generalized method is thoroughly described and extensively tested by Piñol-Ferrer, Lindblad & Fathi (2008, EPIC5), even using the strong barred galaxy NGC 1365. Accordingly, we calculate gas orbits and their velocity and density distribution for an arbitrary gravitational potential.

EPIC5 solves the equations of motion in a solid body rotating, time-independent galactic potential. We assume that the potential is rotating with a pattern speed Ω₀, and we study the system in a corotating frame. We express this arbitrary gravitational potential in polar coordinates, dividing it between an axisymmetric component and a non-axisymmetric perturbation:

\[ \Phi(r, \theta) = \Phi_0(r) + \Phi_1(r, \theta). \]  

The equations of motion are solved assuming the first-order epicyclic approximation (see also Binney & Tremaine 2008, p. 189). Once linearized, we introduce a frictional force proportional to the deviation from circular motion with a damping coefficient, \( \kappa \). (see Lindblad & Lindblad 1994; Wada 1994), for adequate appearance of the resonances.

Then, we introduce \( \xi(t) \) and \( \eta(t) \) as deviations from circular motion, \( (r_0, \theta_0) \),

\[ r = r_0 + \xi \]  
\[ \theta = \theta_0 + (\Omega - \Omega_0) t + \frac{1}{r_0} \eta, \]  

and write the full solution of the linearized equations as

\[ \xi = \frac{c e^{-\kappa t}}{\kappa} \cos \kappa (t - t_0) \]

\[ + \sum_{m=1}^{\infty} \left[ d_m \cos m(\theta - \theta_m) + e_m \sin m(\theta - \theta_m) \right], \]  

\[ \eta = -\frac{2\Omega}{\kappa} \frac{c e^{-\kappa t}}{\kappa} \sin \kappa (t - t_0) \]

\[ + \sum_{m=1}^{\infty} \left[ g_m \sin m(\theta - \theta_m) + f_m \cos m(\theta - \theta_m) \right]. \]  

where \( \theta_m \) is the spiral phase, \( \Omega \) is the circular angular velocity at radius \( r_0 \), \( \kappa \) is the epicyclic frequency which can be expressed as \( \kappa^2 = 4\Omega^2 - 4\lambda A \), \( A \) is the Oort constant, \( \alpha \) and \( \beta \) are functions of \( \Omega \) and \( \kappa \), \( c \) is an arbitrary constant, and \( d_m, e_m, g_m \) and \( f_m \) are given in Piñol-Ferrer et al. (2012). The second terms on the left-hand side of equations (4) and (5) give the forced oscillation due to the perturbing force. The first terms give the damped oscillation with the epicyclic frequency \( \kappa \) around these guiding centres.

With these solutions, EPIC5 computes the deformation of the initially circular orbits of the guiding centre, the velocity fields and the structure created by the arbitrary gravitational potential. Hence, the code pictures a steady-state scenario produced by a weak perturbing potential. All details regarding the mathematical solution can be found in Piñol-Ferrer et al. (2012).

The case of NGC 1097 presents a strong bar with a strength, \( |\Phi_{\text{lin}}|/|\Phi_{\text{bar}}| \), of 0.02. As in the case of NGC 1365 analysed in Piñol-Ferrer et al. (2012) and whose strength is 0.01, although NGC 1097 possesses a strong perturbation, EPIC5 is capable of giving us an estimation of important parameters such as the bar pattern speed and resonance radii by fitting the results to observational data. However, a model based on numerical simulations that accounts for strong gravitational perturbation is needed in order to fully reproduce the physical scenario at play.

3.1 Fourier decomposition of the velocity field

We decompose the observed Fabry-Perot velocity field into Fourier terms up to and including the third order. Numerous authors have shown that this analysis is particularly useful since every component of the velocity Fourier series will bring information about the underlying gravitational potential. The m mode of the perturbing potential will give rise to the \( m = 1 \) and \( m + 1 \) Fourier terms of line-of-sight velocity components (e.g. Canzian 1993; Schoenmakers, Franx & de Zeeuw 1997; Fridman & Khoruzhii 2003). Further discussion on this point can be found in the appendices of van de Ven & Fathi (2010) and Piñol-Ferrer et al. (2012).

The method we use for the decomposition is similar to the one described in Fathi et al. (2005), which we only explain briefly here. We divide the velocity field into concentric elliptical annuli, whose major axis is defined by \( a_{i,j} = a_i + a'_j \), where \( a_i \) is the major axis of each ring, \( dr \) a fixed width of 3 pixels and \( \gamma = 0.5 \). As we expect that rotation is dominant, we start by first only fitting a rotating disc and make a \( \chi^2 \) analysis to obtain the inclination \( i \), systemic velocity, position angle (P.A.) and the central coordinates \( (x_0, y_0) \) of the disc. After fixing these parameters, we make the final \( \chi^2 \) fit to the desired modes (up to and including third order in our case) of the Fourier series decomposition shown in equation (6), where \( V_{\text{los}} \) is the line-of-sight velocity and \( V_{\text{sys}} \) the systemic velocity. We
are assuming in this method that every pixel in the velocity field corresponds to only one position in the inclined disc, and we use a Monte Carlo Bootstrap method for the estimation of the errors of the Fourier series components, considering in this estimation also the error from the observations,

\[ V_{\text{obs}} = V_{\text{sys}} + \sum_{n=1}^{k} \left[ c_n(r) \cos n\theta + s_n(r) \sin n\theta \right] \sin i. \]  

(6)

We obtain the Fourier decomposition of both the GMOS-IFU and the FaNTOmM velocity maps applying this procedure. For the GMOS-IFU data, van de Ven & Fathi (2010) found almost identical parameters. This type of analysis of the entire galaxy-scale of velocity field of NGC 1097 is unprecedented. We find an average kinematic P.A. for the whole galaxy, using FaNTOmM observations, of 128 ± 10°, and a P.A. at the nuclear kpc, from GMOS observations, of 141 ± 8°. This nuclear P.A. is also observed in the fit of the P.A. along radius using the FaNTOmM data, see Fig. 2, middle top panel. We obtain a systematic velocity from the large-scale analysis of 1283 ± 10 km s\(^{-1}\), while we find 1197 ± 5 km s\(^{-1}\) for the nuclear kpc, using the GMOS-IFU data. These discrepancies may be produced by the prominent non-circular motions in the inner region or the lopsided instabilities in the outer disc of the galaxy. However, NGC 1097 cannot be clearly classified as a lopsided galaxy since an estimation of an \( A_1 \) parameter, which is an indicator of this kind of instability (Bournaud et al. 2005), is not significant. Therefore, this highlights the importance of using kinematic data that cover the whole galaxy, since the inner regions present complications in the derivation of these overall galactic parameters. In Fig. 3, we illustrate the comparison between the observations and the recovered map from the rotating component and the full Fourier decomposition.

In addition, we obtain the Fourier decomposition of the \( H_I \) velocity field in order to cross-check with the FaNTOmM velocity field at large radii. This consistency check was made to ensure that the somewhat sparsely covered outer parts of the rotation curve are not suffering from systematic effects due to relatively poor sampling of the galactic rotation curves. The derived \( H_I \) rotation curve confirms the velocity measurements that we have derived from the \( H\alpha \) emission line, Fig. 2, right top panel. The \( H_I \) velocity field analysis gives an estimation of the P.A. of 127 ± 5° and the systemic velocity of 1271 ± 10 km s\(^{-1}\), which is also in concordance with the \( H\alpha \) large-scale analysis.

On the other hand, in Fig. 8 the non-circular velocities of the nuclear region of NGC 1097 are shown, that is, the observed velocity field with the subtraction of the circular velocities used in Section 3.2. As it is explained in Section 3.2, these circular velocities are estimated interpolating the rotational curve derived from FaNTOmM and from GMOS data, which produces a slightly different curve in the inner region from the rotation derived in van de Ven & Fathi (2010). This discrepancy explains the differences that can be observed between our derived non-circular velocities and their map.

### 3.2 Constructing a potential

We derive the gravitational potential of NGC 1097 assuming that it is formed by a dominating axisymmetric component, \( \Phi_0 \), and a weak non-axisymmetric perturbation, \( \Phi_1 \). We express the potential by its Fourier decomposition in polar coordinates, \((r, \theta)\):

\[ \Phi(r, \theta) = \Phi_0(r) + \Phi_1(r, \theta) = \Phi_0(r) - \sum_{m=1}^{n} \Psi_m(r) \cos m(\theta - \vartheta_m(r)), \]  

(7)

where \( \Psi_m(r) \) is the coefficient of the trigonometrical series and \( \vartheta_m(r) \) is the spiral phase.

We estimate the axisymmetric component of the potential from the rotation curve of the galaxy. This rotation curve is derived from the Fourier decomposition of the velocity field, described in Section 3.1. We combine the rotation curve from the large-scale observations with the nuclear \( H\alpha \) data. Then, we interpolate the data points obtained from FaNTOmM and GMOS data sets, see Fig. 2, right top panel. We also smooth this interpolated curve and its derivative in order to get a suave result with \textsc{epic5}. We cannot trust the inner 70–100 pc of the resulting rotation curve since data there present a high level of uncertainty due to dust, non-Gaussian emission lines, high-velocity dispersion, etc. (Fathi et al. 2006).

To derive the large-scale gravitational potential perturbation, we use the deprojected 3.6 \( \mu \)m emission image. We fix the photometric projection parameters at PA = 128° and \( i = 35° \) derived by the kinematic analysis. We rotate the galaxy, placing its bar horizontally and mask the brightest background stars and the satellite from the image, see Fig. 4, left. Before we decompose the image into a Fourier series, we also convolve the 3.6 \( \mu \)m emission image with a two-dimensional 2 kpc sigma Gaussian profile, in order to obtain smoother Fourier components along radius.

When decomposing into its Fourier components, we consider the modes \( m = 0, 2, 3, 4, 5 \) and 6. We exclude the mode \( m = 1 \) in order not to displace the centre of gravity from the centre of the galaxy. That is because \textsc{epic5}, when solving the equation of motion, assumes that the centre of gravity is at rest.

We convert the 3.6 \( \mu \)m surface brightness into surface density using a constant mass-to-light ratio throughout the disc. We analyse the observed rotational curve and how it is recovered for radii between 120 and 180 arcsec (8.4 and 12.6 kpc, respectively, just outside the bar where the dust content is lower) using different ratios. We obtain the best match for a mass-to-light ratio of 1.4 \( M_\odot/L_{\text{3.6} \mu \text{m}} \).

From the Fourier components of the surface density, we derive the perturbing potential following the analysis using Bessel functions described in Binney & Tremaine (2008, chapter 2.6.2) and LLA96. We account for the disc thickness by using a normalized triangle density distribution along the vertical direction in the plane of the disc, i.e.,

\[ F(z) = \begin{cases} \frac{1}{z_0}(1 - \frac{|z|}{z_0}) & \text{for } |z| < z_0, \\ 0 & \text{otherwise}, \end{cases} \]  

(8)

where we assume a \( z_0 \) scale parameter equal to 1 kpc, the 13 per cent of the bar which is in concordance with a rotation velocity of 300 km s\(^{-1}\) (van der Kruit & Freeman 2011).

For the central 4 arcsec the potential was derived from the GMOS-IFU data in order to get a more accurate potential across the circumnuclear region (van de Ven & Fathi 2010). We combine the large-scale gravitational potential, for radius larger than 2 kpc, with the nuclear scale potential from GMOS-IFU data. Then, we interpolate between the nuclear potential and the large-scale potential, for radii between ∼0.4 to 2 kpc. In this transition region, the interpolation is the source of major uncertainty. We place the nuclear spiral
NGC 1097, pattern speed and circumnuclear ring

Figure 2. Fourier expansion for the high-resolution ionized gas velocity field of NGC 1097 up to the third mode. We have combined the components derived from the nuclear region (GMOS-IFU data) and from the large-scale galaxy (FaNTOmM data). We fix the systematic velocity and the kinematic P.A. in the analysis of FaNTOmM data as shown in the two first upper graphs. In the third upper graph, we show the derived rotation curve as a combination of the two data sets GMOS-IFU and FaNTOmM together with the H I rotation curve. In the two lower rows, we present the different Fourier terms with linear and logarithmic x-axes.

arms at an angle that gives the best comparison between the observed non-circular velocities and those in our analytic model. We observe that the $m = 2$ mode from the GMOS data is approximately a factor 1.5 lower than the minimum of the perturbing potential derived from the Fabry-Perot data, see Fig. 5. That means that the derived gravitational potential in the nuclear region is much stronger that for larger radii in the galaxy. It is likely that this is a real effect, meaning that the GMOS data are more powerful in picking up the
strength of the perturbing potential in the nuclear part. In Fig. 5, \( \Psi_1(r) \) is the coefficient of the trigonometric series and \( \vartheta_m \) is the spiral phase, once that nuclear and large-scale potentials have been combined.

### 3.3 EPIC5: an analytic fit to NGC 1097 data

We model the NGC 1097 data, by introducing the gravitational potential estimated as described in Section 3.2. To finalize the model, we need to know the bar pattern speed. One way to estimate the pattern using this code is comparing the observed velocity field presented in Section 2, Fig. 1, right-hand panel, with velocity fields generated by EPIC5 using different pattern speeds. We realize a \( \chi^2 \) study, varying the pattern speed and damping coefficients, fitting the velocity field generated by EPIC5 projected on the plane of the galaxy, to the observed velocity field. We use the FaNTOmM data to fit the large-scale structure, using exactly the potential described in Section 3.2, and the GMOS data only to fit the nuclear region, using the potential derived in van de Ven & Fathi (2010). From the large-scale fit, after a \( \chi^2 \) analysis for eight different combinations of the four variables involved, we obtain a pattern speed of \( \Omega_p = 36 \pm 2 \text{ km s}^{-1} \text{kpc}^{-1} \). We estimate the error of the pattern speed considering the 1σ confidence level. The orbits of our model are shown in Fig. 6.

Besides the potential and the pattern speed, EPIC5 needs three damping coefficients, at corotation and inner/outer Lindblad resonances (ILR/OLR), as inputs in order to generate the solution. In EPIC5, the damping coefficient that avoids singularities at the Lindblad resonances has been found to have a linear dependence on the radius. However, in the case of the strong barred galaxy NGC 1097, much larger damping coefficient at nuclear scales are needed compared with the outer ranges. For this reason, we choose the damping...
coefficient to be proportional to the angular frequency along radius. We use a range of damping coefficients for which the gas orbits do not cross.

While we see in Figs 7 and 8 that EPIC5 generate approximate NGC 1097 kinematics, we note that the non-circular velocity amplitudes are not objective since they depend on the adopted damping coefficient. Since NGC 1097 hosts a strong bar and EPIC5 assumes a weak perturbation, high-damping coefficients are needed to ‘dampen’ the model non-circular velocity amplitudes. We think that the presence of a strong bar when assuming a weak perturbation also explains the mismatched features inside the corotation radius (CR), the much straighter observed density ‘lanes’ are not aligned by the lanes in the model, and hence, the observed location for the shock loci is displaced. However, other explanations such as a scenario where the spiral arms are decoupled with the bar could also contribute to some of the discrepancies between the model and observations.

4 THE PATTERN SPEED OF NGC 1097
The estimation of the pattern speed of NGC 1097 using EPIC5 gives a value of $36 \pm 2\,\text{km s}^{-1}\,\text{kpc}^{-1}$. This frequency places corotation...
Figure 7. Black ellipses mark the resonance radii and the corotation (iILR at 90 pc, oILR at 2.9 kpc, CR at 8.6 kpc and OLR at 14.9 kpc). Upper left: observed velocity field observed. Upper right: velocity field generated by EPIC for a pattern speed of 36 km s$^{-1}$ kpc$^{-1}$. Middle left: observed non-circular velocities. Middle right: model non-circular velocities. Lower left: observed H$\alpha$ intensity map. Lower right: surface density map generated by EPIC, where the ratio between the perturbed and unperturbed surface density is illustrated. The model non-circular velocity map clearly displays the expected three-fold symmetric non-circular motions due to the presence of an $m = 2$ gravitational perturbation outside corotation, and a pair of receding and approaching arms close to the oILR.
at 8.6 ± 0.5 kpc, two ILRs at 60 ± 5 pc and 2.9 ± 0.1 kpc and the OLR at 14.9 ± 0.9 kpc (see Fig. 9). These resonance locations are obtained assuming a linear approximation; therefore, they may slightly change in the presence of a strong bar. Their location is marked in Fig. 7 by black ellipses, where one can observe that the corotation is placed around the end of the bar and that the nuclear star-forming ring, with radius around 1 kpc, is located between the two ILRs.

The errors of the resonance positions are functions of the errors of the rotation curve and its derivatives. However, we have estimated these errors taking into account the error in the pattern speed, which gives an uncertainty at least one order of magnitude larger. Still the error of the pattern speed may be underestimated if systematic errors are involved, which would also increase the errors on the resonance positions. Another error source that we have to mention is the uncertainty in the rotational curve between ∼1.5 and 3 kpc due to the lack of pixels covering the region of interest.

The pattern speed value derived using EPIC5 is in full agreement with the value used in van de Ven & Fathi (2010) and with the value obtained by using the model-independent Tremaine–Weinberg method (Tremaine & Weinberg 1984). The latter is the result of the Tremaine–Weinberg method applied to the FaNTomM velocity field weighted with the Spitzer image (Fathi et al. 2009), i.e. 30 ± 8 km s⁻¹ kpc⁻¹.

Alternatively, we use the phase-reversal method (Font et al. 2011) in order to determine the CR and the associated bar pattern speed. In short, the method locates the π phase reversals of the non-circular velocities. This way, we obtain the distribution of the phase reversals as a function of the galactocentric radius. The radial distribution shows several peaks, which can be fitted with standard Gaussian functions. Assuming that streaming velocities change sign at the CR, we can identify the maximum in the radial distribution histogram with the CR. Applying the phase-reversal method to the residual velocity map of NGC 1097, the strongest peak of the phase-reversal histogram is found at a radius of 7.7 ± 0.2 kpc, and the corresponding pattern speed is 39.5 ± 1.1 km s⁻¹ kpc⁻¹. It should be noted that the errors in the latter value only include formal errors and that they are expected to be larger when including the systemic uncertainties involved. Nevertheless, this is a good match to the value of the pattern speed derived by means of the analytic dynamical model (see Section 3).

In order to compare the estimated pattern speed of this galaxy with simulations, we estimate the bar length, a, of NGC 1097. We study this parameter by looking at the ellipticity of the galaxy, at the phase shift of the second Fourier component and at the contrast parameter defined by Ohta, Hamabe & Wakamatsu (1990). We find that a is approximately 7.9 ± 0.6 kpc. This gives a ratio of the radius of corotation, CR-over-bar length, R = R_{cr}/a, of 1.0–1.2, which corresponds to a fast bar. From numerical models, it is known that in barred galaxies R has a values of 1.2 ± 2 (see e.g. Athanassoula 1992), which is in concordance with our estimations for NGC 1097.

On the other hand, since it is widely believed that nuclear rings form at ILRs (e.g. Buta & Combes 1996), a faster pattern speed could have been expected. However, based on both the ionized gas and the neutral gas rotation curve, we find that a pattern speed that would locate the nuclear ring at the outer ILR (oILR), will locate the CR in an unrealistically smaller radius in the galaxy and consequently produce R ≪ 0.9 (R ≈ 0.3).
5 COMPARISON OF OBSERVATIONS AND THE MODEL

To compare our high-resolution Fabry-Perot kinematic maps with the modelled velocity fields, we first look at the non-circular velocity maps. Figs 7 and 8 show the observed velocity field, non-circular velocities and Hα luminosities of NGC 1097 together with the analytically modelled velocities and densities. At large scales, our model follows the outer spiral arms of the galaxy until the end, almost closing after the OLR. Furthermore, both the observed and model non-circular velocity fields reveal three kinematic spiral arms after the CR, at 8.6 ± 0.5 kpc. These arms are produced by the bi-symmetric component of the gravitational potential. Inside corotation, our model is able to reproduce the expected velocity jump linking the end of the bar with the outer galactic spiral arms. This is consistent with similar velocity jumps found by Patsis (2006). Moreover, the correlation between model and observations here becomes less evident than after corotation since our model presents the dust lane rotated with respect to the central lane of NGC 1097. This may be due to the fact that EPSC5 reproduces a weak bar model while the bar in NGC 1097 would easily qualify as a strong bar, and it is expected that dust lanes are more straight as they get stronger (Athanassoula 1992; Knappen, Pérez-Ramírez & Laine 2002; Comerón et al. 2009). Also in the bar region, although the modelled dust lanes are rotated with respect to the observed central ones, we find signatures of strong shocks along the front edge of the bar, where the gas crossing the bar sharply bends inwards along the dust lanes towards the centre. They are very important since they bend the orbits across the bar sharply inwards and thus help to feed the nuclear region.

We further look into the central region by comparing the analytic model with the GMOS-IFU velocity field. Our model reproduces the density structures corresponding to the two strong nuclear spiral arms found by van de Ven & Fathi (2010). In the density panels of Figs 7 and 8, the modelled surface density is plotted as the ratio between the perturbed and unperturbed surface densities. In the inner tens of parsecs, two spiral arms are modelled. These arms are not obvious in the ionized gas maps, predominantly due to strong contamination from the diffuse ionized gas emission. Nevertheless, two clear nuclear spiral arms are seen in wavelet analysis maps presented by Lou et al. (2001, their fig. 1) and the structure map shown by (Fathi et al. 2006, middle panel of their fig. 3). We further note that Prieto, Maciejewski & Reunanen (2005) argued for the presence of three spiral arms at the centre of this galaxy. However, quantitative kinematic analysis highlights the presence of three kinematic spiral arms (i.e. two arms in morphology), in van de Ven & Fathi (2010). In our kinematic analysis shown in Fig. 8, using the same data set, these three kinematic spiral arms are not as clear as in their map due to the slightly different rotational curve used. Moreover, our model predicts one kinematic spiral arm, as shown in the second panel of Fig. 8. That difference between the observations and the model is produced by the fact that in the observations, the shape of the non-circular velocities depend on the derived rotation curve that we are subtracting. That is because in these circular velocities, part of the \( m = 1 \) component is hidden and this is the main reason why three kinematic spiral arms are observed instead of one as theory indicates. In our modelled non-circular velocity map, we observe one arm in the absence of hidden \( m = 1 \) contribution in the rotation curve. In addition, looking at our modelled non-circular velocity map, we can observe a \( m = 3 \) contribution hidden in the map that is seen due to the uneven continuity in the beginning of the one spiral. This predominance of the \( m = 3 \) and \( m = 1 \) Fourier terms of the sight velocity in the non-circular velocities supports the idea of a situation in which the gravitational potential is bi-symmetrically perturbed (see first paragraph of Section 3.1 above here).

Observations also reveal that the nuclear spiral arms start at the nuclear ring located at around 1 kpc. In our model, these arms also start at the position of the nuclear ring, which is a structure that is the prolongation of the dust lanes. Furthermore, the ring is not entirely closed in our model and it is not located anywhere near the location of any main resonances.

5.1 Is the ring migrating inwards?

Our analysis suggests that what is commonly referred to as the circumnuclear ring in NGC 1097 is a region of enhanced star formation activity at the inner ends of the dust lanes that cuts through the major axis of the primary bar, crossing the oILR and connecting with the nuclear spiral arms.

The understanding of the exact location of the ring is important in order to comprehend the effects of secular evolution of NGC 1097. Circumnuclear rings are commonly thought to be located at or close to the ILRs (e.g. Byrd et al. 1994; Elmegreen 1994; Buta & Combes 1996). However, considering the locations of the inner ILRs (iILR) and oILRs in our epicyclic model, this ring seems not to be located near either, but in a region significantly distant from the two. The resonance radii that we have described are only valid under a weak non-axisymmetric perturbation, while NGC 1097 has a strong bar. However, this estimation for the resonance radii are likely to be a useful indication (Knappen et al. 1995; Mazzuca et al. 2011). This is the same situation found in other galaxies like NGC 1068 (Telesco & Decher 1988), M100 (Arsenault et al. 1988) or NGC 3504 (Kenney, Carlstrom & Young 1993).

Another preferred general location for circumnuclear rings is the turnover location in the rotation curve, where the rotation curve goes from an initial steeply raising to a flatter segment (e.g. Buta & Combes 1996, and references therein). The circumnuclear star-forming ring of NGC 1097 is located at \( \sim 1 \) kpc which approximately coincides with the turnover radius (see Wolstencroft & Scheppm 1979, and Fig. 2, right top panel). Hence, our results agree with this situation but place the circumnuclear ring between the two ILRs. This may point out an inward migration of the ring from the oILR.

This scenario has been predicted by Fukuda, Habe & Wada (2000), Regan & Teuben (2003) and van de Ven & Chang (2009), who have shown evidence, by simulations or analytical studies, that rings could form at a Lindblad resonance, but that they may migrate inwards through the galactic disc. These studies find that the migration of the circumnuclear ring is produced by the inflowing gas from the dust lane to the ring, by the underlined gravitational potential and by the viscosity. However, tests made by Regan & Teuben (2003) in their simulations seem to indicate that the main responsible mechanism is the gas flowing down from the dust lanes. Notably, the latter study predicts that when the ring is not located at a Lindblad resonance, inward migration may well lead to strong star formation due to gas accumulation at its edges producing enhancements in the density and favouring unstable scenarios against self-gravitation. Hence, as the ring moves, the star formation along the ring changes from probably presenting an aged azimuthal gradient, produced by a location of the star formation at the connection points of the dust lanes with the ring, to a randomly distributed star formation (van de Ven & Chang 2009). This scenario is also confirmed by the randomly distributed and strong star formation...
found in the circumnuclear ring of NGC 1097 with the no-clear age azimuthal gradient (Sandstrom et al. 2010; Hsieh et al. 2011; Piñol-Ferrer et al. 2011).

| Table 2. A summary of the physical parameters derived in this work. |
|------------------|------------------|
| NGC 1097         |                  |
| $V_{\text{sys}}$ | 1283 ± 10 km s$^{-1}$ |
| P.A.             | 128 ± 10$^\circ$ |
| Bar length       | 7.9 ± 0.6 kpc     |
| Pattern speed (Phase-reversal method)$^a$ | 39.5 ± 1.1 km s$^{-1}$ kpc$^{-1}$ |
| Pattern speed (rcm:5) | 36 ± 2 km s$^{-1}$ kpc$^{-1}$ |
| Pattern speed (TW method)$^b$ | 30 ± 8 km s$^{-1}$ kpc$^{-1}$ |
| CR               | 8.6 ± 0.5 kpc     |
| iILR and oILR    | 60 ± 5 pc and 2.9 ± 0.1 kpc |
| OLR              | 14.9 ± 0.9 kpc    |

$^a$Font et al. (2011).
$^b$Tremaine & Weinberg (1984); Fathi et al. (2009).

6 CONCLUSIONS

We present here an unprecedented galactic-scale dynamical model of the kinematics and morphology of NGC 1097. Our analytic model has been constructed by deriving the gravitational potential of NGC 1097 from the old stellar population and observed rotation curve, which we use to generate the solution of the equations of motion of the gas in this galaxy, assuming the epicyclic approximation. We verify the model by applying it to high-resolution Fabry-Perot interferometric data covering the entire galaxy. We further zoom into the central few hundred parsecs by using high spatial resolution (0.1 arcsec pix$^{-1}$) two-dimensional spectroscopy of the nuclear central kiloparsec. The calculation of the solution of the equations of motion is done by using our own customized code $\text{epic5}$.\footnote{The $\text{epic5}$ code can be obtained from npi@astro.su.se.} A summary of the physical parameters derived in the model are shown in Table 2.

We find that the bar in NGC 1097 has a radius of 7.9 ± 0.6 kpc and that it is rotating with a pattern speed of 36 ± 2 km s$^{-1}$ kpc$^{-1}$. This pattern speed places the CR at 8.6 ± 0.5 kpc, the OLR at 14.9 ± 0.9 kpc and two ILRs at 60 ± 5 pc and 2.9 ± 0.1 kpc, based on the epicyclic approximation. These derivations lead to a ratio of CR-over-bar length, $R_c/R_b$, of 1.0–1.2, which is in concordance with numerical simulations and models of barred galaxies (e.g. Athanassoula 1992). Our analytic dynamical model reproduces all the significant kinematic and structural signatures:

(i) The outer two spiral arms that are created at corotation and almost close after the OLR. Also the related three-fold symmetric non-circular motions are recovered in our model.

(ii) The expected velocity jump linking the end of the bar with the outer galactic spiral arms, consistent with similar velocity jumps found by Patsis (2006).

(iii) The kinematics produced by two nuclear spiral arms seen in wavelet analysis maps presented by Lou et al. (2001, their fig. 1), the structure map shown in Fathi et al. (2006) and the kinematics study presented in van de Ven & Fathi (2010).

(iv) The position of the starting point of the nuclear spiral arms.

(v) The location of the circumnuclear ring.

Our model also reveals that the circumnuclear ring of this galaxy is not located near any of the ILR radii, as commonly expected for nuclear rings in barred galaxies. We find compelling evidence that the ring is located in the region between the iILRs and oILRs. This may indicate that the ring once formed at the oILR radius, and it has been migrating towards the centre of the galactic gravitational potential. The plausibility of such ring migration has been previously predicted by Fukuda et al. (2000), Regan & Teuben (2003) and van de Ven & Chang (2009).

ACKNOWLEDGEMENTS

We wish to thank Per-Olof Lindblad and Panos Patsis for their insightful and invaluable comments and James Higdon for kindly providing his H$^\alpha$ data. NP-F is supported by the Nordic Optical Telescope Scientific Association (NOTSA). KF acknowledges support from the Swedish Research Council (Vetenskapsrådet) and the Swedish Royal Academy of Sciences’ Crafoord Foundation. KF also acknowledges the hospitality of the Max-Planck-Institut für extraterrestrische Physik (MPE) where parts of this work were carried out.

REFERENCES

Arsenault R., Boulesteix J., Georgelin Y., Roy J.-R., 1988, A&A, 200, 29
Athanassoula E., 1992, MNRAS, 259, 345
Baker A. J., 2000, PhD thesis, California Institute of Technology
Binney J., Tremaine S., 2008, Galactic Dynamics, 2nd ed. Princeton Univ. Press, Princeton, NJ
Boone F. et al., 2007, A&A, 471, 113
Bournaud F., Combes F., Jog C. J., Puera I., 2005, A&A, 438, 507
Buta R., Combes F., 1996, Fundum. Cosm. Phys., 17, 95
Byrd G., Rautiainen P., Salo H., Buta R., Crocher D. A., 1994, AJ, 108, 476
Canzian B., 1993, ApJ, 414, 487
Combes F., 2001, in Aretxaga I., Kunth D., M´ujica R., eds, Advanced Lectures on the Starburst-AGN Connection. World Scientific Press, Singapore, p. 223
Comer´on S., Mart´ınez-Valpuesta I., Knappen J. H., Beckman J. E., 2009, ApJ, 706, L256
Davies R. I., Muller S´anchez F., Genzel R., Tacconi L. J., Hicks E. K. S., Friedrich S., Sternberg A., 2007, ApJ, 671, 1388
Davies R. I., Maciejewski W., Hicks E. K. S., Tacconi L. J., Genzel R., Engel H., 2009, ApJ, 702, 114
Dicaire I. et al., 2008, MNRAS, 385, 553
Elmegreen B. G., 1994, ApJ, 425, L73
Erwin P., 2004, A&A, 415, 941
Fathi K., van den Ven G., Peletier R. F., Emsellem E., Fal´con-Barroso J., Cappellari M., de Zeeuw T., 2005, MNRAS, 364, 773
Fathi K., Storchi-Bergmann T., Riffel R. A., Winge C., Axon D. J., Robinson A., Capetti A., Marconi A., 2006, ApJ, 641, L25
Fathi K., Beckman J. E., Piñol-Ferrer N., Hernandez O., Mart´ınez-Valpuesta I., Carignan C., 2009, ApJ, 704, 1657
Font J., Beckman J. E., Fathi K., Guti´errez L., Hernandez O., 2011, ApJ, 741, L14
Fridman A. M., Khoruzhii O. V., 2003, Space Sci. Rev., 105, 1
Fukuda H., Habe A., Wada K., 2000, ApJ, 529, 109
García-Burillo S., Combes F., Schinnerer E., Boone H., Hunt L. K., 2005, A&A, 441, 1011
Hernandez O., Gach J.-L., Carignan C., Boulesteix J., 2003, in Iye M., Moorwood A. F. M., eds, Proc. SPIE Vol. 4841, Fabry Perot of New Technology for the Observatoire du mont Megantic. SPIE, Bellingham, p. 1472
Hicks E. K. S., Davies R. I., Malkan M. A., Genzel R., Tacconi L. J., Müller Sanchez F., Sternberg A., 2009, ApJ, 696, 448
Higdon J. L., Wallin J. F., 2003, ApJ, 585, 281
Hsieh P.-Y., Matsushita S., Liu G., Ho P. T. P., Oi N., Wu Y.-L., 2011, ApJ, 736, 129
Hummel E., van der Hulst J. M., Kennicutt R. C., Keel W. C., 1990, A&A, 236, 333
Kennicutt J. D. P., Carlstrom J. E., Young J. S., 1993, ApJ, 418, 687
Kennicutt J. et al., 2003, PASP, 115, 928
Knapen J. H., Beckman J. E., Heller C. H., Shlosman I., de Jong R. S., 1995, ApJ, 454, 623
Knapen J. H., Pérez-Ramírez D., Laine S., 2002, MNRAS, 337, 808
Lindblad P. O., Lindblad P. A. B., 1994, in King I. R., ed., ASP Conf. Ser. Vol. 66, Physics of the Gaseous and Stellar Disks of the Galaxy. Astron. Soc. Pac., San Francisco, p. 29
Lindblad P. A. B., Lindblad P. O., Athanassoula E., 1996, A&A, 313, 65 (LLA96)
Lou Y.-Q., Yuan C., Fan Z., Leon S., 2001, ApJ, 553, L35
Martini P., Regan M. W., Mulchaey J. S., Pogge R. W., 2003, ApJ, 589, 774
Mazzuca L. M., Swaters R. A., Knapen J. H., Veilleux S., 2011, ApJ, 739, 104
Ohta K., Hamabe M., Wakamatsu K.-I., 1990, ApJ, 357, 71
Patsis P. A., 2006, MNRAS, 369, L56
Piñol-Ferrer N., Fathi K., Lundgren A., van de Ven G., 2011, MNRAS, 414, 529
Piñol-Ferrer N., Lindblad P. O., Fathi K., 2012, MNRAS, 421, 1089
Prieto M. A., Maciejewski W., Reunanen J., 2005, AJ, 130, 1472
Regan M. W., Teuben P., 2003, ApJ, 582, 723
Sakamoto K., Okumura S. K., Ishizuki S., Scoville N. Z., 1999, ApJS, 124, 403
Sanders R. H., Huntley J. M., 1976, ApJ, 209, 53
Sandstrom K. et al., 2010, A&A, 518, L59
Schoenmakers R. H. M., Franx M., de Zeeuw P. T., 1997, MNRAS, 292, 349
Schwarz M. P., 1984, MNRAS, 209, 93
Sersic J. L., 1958, The Observatory, 78, 123
Shlosman I., Frank J., Begelman M. C., 1989, Nature, 338, 45
Storchi-Bergmann T., Baldwin J. A., Wilson A. S., 1993, ApJ, 410, L11
Storchi-Bergmann T. et al., 2003, ApJ, 598, 956
Telesco C. M., Decher R., 1988, ApJ, 334, 573
Tremaine S., Weinberg M. D., 1984, ApJ, 282, L5
Tully R. B., 1988, Nearby Galaxies Catalog. Cambridge Univ. Press, Cambridge, p. 221
van de Ven G., Chang P., 2009, ApJ, 697, 619
van de Ven G., Fathi K., 2010, ApJ, 723, 767
van der Kruit P. C., Freeman K. C., 2011, ARA&A, 49, 301
Wada K., 1994, PASJ, 46, 165
Wolstencroft R. D., Schmempp W. V., 1979, N.Z. J. Science, 22, 325

This paper has been typeset from a TeX/LaTeX file prepared by the author.