Physical condition of the molecular gas at the centre of NGC 1097

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ABSTRACT
We have used the $X_{\text{CO}}$ conversion factor, local thermodynamic equilibrium and large velocity gradient approximation to parametrize the cold and warm phases of the interstellar medium from five different low transitions of the CO molecule in the central 21 arcsec (kpc) region of NGC 1097. We have applied a one-component model and derived a typical kinetic temperature of about 33 K, a molecular hydrogen density of $4.9 \times 10^7 \text{M}_\odot \text{pc}^{-2}$ and a CO column density of $1.2 \times 10^{-21} \text{M}_\odot \text{pc}^{-2}$. A two-component model results in 85 per cent cold-to-total gas fraction in the presence of a 90 K warm counterpart. Furthermore, we ‘resolve’ the spatially unresolved single-dish observations by selecting velocity channels that in an interferometric velocity map correspond to specific regions. We have selected five such regions and found that the physical properties in these regions are comparable to those derived from the full line profile. This implies that the central kpc of NGC 1097 is rather homogeneous in nature and, although the regions are not uniquely located within the ring, the star formation along the ring is homogeneously distributed (in agreement with recent Herschel observations). We have further revised the mass-inflow rate on to the supermassive black hole in this prototype low-ionization nuclear emission-line region/Seyfert 1 galaxy and found that accounting for the total interstellar medium and applying a careful contribution of the disc thickness and corresponding stability criterion increases the previous estimations by a factor of 10. Finally, we have calculated the $X_{\text{CO}}$ conversion factor for the centre of NGC 1097 using an independent estimation of the surface density to the CO emission and obtained $X_{\text{CO}} = (2.8 \pm 0.5) \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1}$ at a radius 10.5 arcsec and $X_{\text{CO}} = (5.0 \pm 0.5) \times 10^{20} \text{cm}^{-2} (\text{K km s}^{-1})^{-1}$ at a radius 7.5 arcsec. With the approach and analysis described in this paper, we have demonstrated that important physical properties can be derived to a resolution beyond the single-dish resolution element; however, caution is necessary while interpreting the results.

Key words: galaxies: fundamental parameters – galaxies: individual: NGC 1097.

1 INTRODUCTION

The connection between the star formation at centres of galaxies and the onset of the nuclear activity involves processes still not completely understood. In many cases, the majority of the star formation in galaxies is located in circumnuclear rings and the most-extended mechanism for fueling them and generating densities high enough to form stars is believed to be non-axisymmetric perturbations, such as bars or tidal interactions. In the presence of a bar, the overdensity of a gas may occur in resonances, like the inner Lindblad resonance (ILR) for an inner ring (e.g. Combes & Gerin 1985; Athanassoula 1992; Wada 1994). Once the gas is accumulated in the ring, there are two main hypothetical scenarios for the formation of stars in the ring: (1) the star formation produced by gravitational instabilities in different giant clouds placed randomly along the ring (Elmegreen 1994); and (2) quasi-instantaneous star formation in two regions with overdensities, usually the connection points of the dust lanes of the bar with the ring, followed by the migration of the star forming knots along the rotation velocity of the disc, producing an age gradient along the ring (Böker et al. 2008).

The study of star formation locations is typically done by observing the Hα or radio continuum emission. In addition, it is possible to use direct measurements of the gas column density ($\Sigma_{\text{gas}} = \Sigma_{\text{HI}} + \Sigma_{\text{H}_2}$) to which the star formation rate per unit area, $\Sigma_{\text{SFR}}$, is empirically related by the Schmidt law (Schmidt 1959; Kennicutt 1989). One aim of this paper is to measure the molecular gas column density in order to characterize the star formation.

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along the 1-kpc ring of the nearby prototype low-ionization nuclear emission-line region (LINER)/Seyfert 1 (Sy1) barred galaxy NGC 1097, estimated through CO observations.

The fuelling of the nuclear and/or circumnuclear activity in barred galaxies is driven by the bar itself due to the loss of angular momentum along the dust lanes (e.g. Athanassoula 1992); however, the fate of the inflow mass after passing the ILR is still unsolved. Several mechanisms have been inferred to explain the fate of the inflowing gas. One proposed mechanism is the coupling of nested bars inside the ILR of primary bars, transporting gas and stars towards the centre (e.g. Shlosman, Frank & Begelman 1989; Englmaier & Shlosman 2004). This mechanism is not completely established since there are other studies which show that nested bars are not allowed to carry material to the inner few parsec of galaxies (Maciejewski et al. 2002). Another proposed mechanism is the inflow along nuclear spiral arms, which are connected with the dust lanes of the primary bar (e.g. Englmaier & Shlosman 2000; Maciejewski et al. 2002; Maciejewski 2004). These arms have a very low density contrast compared with the ambient interarm regions, only by about 10 per cent (Englmaier & Shlosman 2000), and present a wide variety of observed morphologies. Morphologically, nuclear spirals are divided into two main categories, chaotic spirals and symmetric or grand design spirals, for which different formation mechanisms have been proposed (e.g. Elmegreen et al. 1998; Englmaier & Shlosman 2000; Maciejewski et al. 2002). In the presence of a central supermassive black hole (SMBH), spiral shocks can extend all the way to its vicinity and generate the gas inflow compatible with the accretion rates observed in local active galactic nuclei. (e.g. morphologically by Martini et al. 2003 and kinematically by Fathi et al. 2006).

NGC 1097 is an excellent candidate to study the inflow processes driven by the bar; however, the lack of direct measurements of the physical conditions of the interstellar gas in the circumnuclear regions has complicated the matter. Optical (van de Ven & Fathi 2010), near-infrared (Kotilainen et al. 2000; Davies et al. 2009), radio continuum (Beck et al. 2005), CO transitions with radio interferometers and single-dish observations (Kohno et al. 2003; Petitpas & Wilson 2003 Hsieh et al. 2008) and far-infrared observations (Beirão et al. 2010; Sandstrom et al. 2010) have been performed for the 1-kpc starburst ring. Moreover, the processes involved in the star formation in the ring and the estimation of the mass-accretion rate towards its (1.2 ± 0.2) × 10⁸ M⊙ SMBH (Lewis & Eracleous 2006) are to date inconclusive. As a second goal, we shed light on the total gas mass in the region inside the ring and apply several methods to better understand the physical state of the cold+warm (< 150 K) gas in the circumnuclear kpc of NGC 1097.

We use archival data combined with our own single-dish observations of the molecular gas in the circumnuclear regions using the Atacama Pathfinder EXperiment (APEX) telescope. The data are used with two different line ratio modelling methods to obtain a new estimation of the physical properties of the gas and the mass-accretion rate towards the SMBH to compare with the previous estimations. Moreover, we derive the molecular gas physical conditions along regions with comparable line-of-sight velocities and in this way, we override the limited spatial resolution of the single-dish observations.

In Section 2, we present the observations and data reduction. In Section 3, we explain all the analysis done for estimating the line ratios and for studying the physical properties using the X\textsubscript{CO} conversion factor, a local thermal equilibrium and a large velocity gradient (LVG) approximation for the inner kpc of NGC 1097. In Section 4, we explain the analysis made within the ring and discuss the result obtained there, in Section 5 we discuss the mass-inflow rate towards the inner parsecs and in Section 6 we present a study of the real X\textsubscript{CO} conversion factor value for this galaxy. Finally, we conclude in Section 7.

### 2 OBSERVATIONS AND DATA REDUCTION

On 2008 June 27, we observed 12CO(3–2) and 13CO(3–2) in one pointing at the centre of NGC 1097 with the APEX on Llano de Chajnantor, Chile, using the APEX-2 receiver. The half-power beam width (HPBW) is 18 arcsec at 345.8 GHz and 18.8 arcsec at 330 GHz. In addition, we mapped 12CO(3–2) along the primary bar of NGC 1097 on 2009 July 7 by using the same set-up. We mapped the bar with an array of 9 × 3 points. We scaled the antenna temperature by adopting the value for ηMB presented in the APEX web page of 0.73. During the reduction of the spectra, we subtracted a first-order baseline from the profiles. Lines are shown in Fig. 1.

Our data have been combined with published single-dish and interferometric data from the centre of this galaxy: 12CO(1–0) from Kohno et al. (2003) with a HPBW of 15 arcsec observed with

![Figure 1. The different observations with corresponding transitions indicated in each panel at 21-arcsec resolution (black curves) as described in Section 2. The original 15-arcsec 12CO(1–0), 18-arcsec 12CO(3–2) and mapped 13CO(3–2) lines are overplotted with the red dotted curves.](https://academic.oup.com/mnras/article-abstract/414/1/529/1094595)
the Nobeyama Radio Observatory. $^{12}$CO(2–1) and $^{13}$CO(2–1) from Petitas & Wilson (2003) with a HPBW of 21 arcsec observed with the James Clerk Maxwell Telescope and $^{12}$CO(1–0) observed with the Nobeyama Millimetre Array (Kohno et al. 2003). All the auxiliary data were convolved to the common beam size of 21 arcsec and we discuss the $^{12}$CO(1–0) case separately in the following section. For the $^{13}$CO(3–2) transition, we estimated the ratio between $^{12}$CO(3–2) and $^{13}$CO(3–2), both with a beam size of 18 arcsec, assuming that the ratio changes only marginally between 18–21 arcsec beam sizes. We further observed the $^{13}$CO(3–2) transition in additional nine positions around the central 18.8 arcsec, with the APEX telescope, on 2010 October 8 and confirmed the validity of the bottom right-hand panel of Fig. 1 as representative of a 21-arcsec observation.

2.1 $^{12}$CO(1–0)
We combined the $^{12}$CO(1–0) single-dish line with the $^{12}$CO(1–0) interferometric data from Kohno et al. (2003) to estimate the missing flux. The interferometric data were thus convolved to the resolution of the single-dish observations and a spectral line from the central beam of the galaxy was extracted, resulting in a missing flux of 7.7 per cent. Given the relatively marginal missing flux (<10 per cent), emission lines corresponding to the 21-arcsec beam could be obtained simply by the co-addition of the interferometric data.

Furthermore, we improve our estimation of the line using the average of two different methods to recover the 21-arcsec line. Method 1: adding 7.7 per cent to the co-added interferometric data and Method 2: by calculating the missing flux for every channel of the line with a 15-arcsec beam and adding the corresponding missing flux (per channel) to the corresponding channel of the generated 21-arcsec line. Following these tests, for our analysis, we use the average of these two cases, for which a flux error can be obtained as the mean of the standard deviations of every channel.

3 THE UNRESOLVED CENTRAL kpc

3.1 Line-ratio estimation

All lines were binned to the velocity sampling of 26 km s$^{-1}$ to match the largest sampling available with us. We neglected channels with a signal-to-noise ratio (S/N) smaller than 3 and calculated the ratio of the different lines by averaging the ratios between temperatures of every channel. The corresponding errors were then the standard deviation of this average. We also estimated the ratios using the velocity-integrated intensity of every line and found that they agree very well with the previous measurement. The results are shown in the Tables 1 and 2.

### Table 1. Spectral line parameters and specifications.

| Line          | Beam size (HPBW) (arcsec) | Intensity $\int T_{mb} dV$ (K km s$^{-1}$) | Reference                        |
|---------------|---------------------------|-------------------------------------------|----------------------------------|
| $^{12}$CO(1–0)| 21/15                     | 89 ± 9/96 ± 2.8$^a$                       | Kohno et al. (2003)              |
| $^{12}$CO(2–1)| 21                        | 110 ± 7                                   | Petitas & Wilson (2003) (121 ± 1 K km s$^{-1}$)$^a$ |
| $^{12}$CO(3–2)| 21/18                     | 91 ± 6/102 ± 4 $^a$                       | APEX data$^b$                    |
| $^{13}$CO(2–1)| 21                        | 14 ± 2                                     | APEX data$^b$                    |
| $^{13}$CO(3–2)| 18/21                     | 7 ± 3/6 ± 3 $^a$                          | APEX data$^b$                    |

$^a$Previous estimation of the intensities by the corresponding author.
$^b$Petitas & Wilson (2003) derived 121.7 ± 0.5 K km s$^{-1}$ for a 21-arcsec beam.

The errors which contribute to the line measurements are: (i) the rms; (ii) the error due to bad pointing; (iii) the missing flux of $^{12}$CO(1–0); and (iv) the uncertainty of the main beam efficiency $\eta_{MB}$ and that of the main beam size $\theta_{MB}$. Our data reduction and resampling method provides a good estimation of the rms and missing flux errors, and the errors due to the beam size and efficiency, together, are estimated to be of the order of 10 per cent (at most 10 per cent for the main beam efficiency and 0.05 per cent for the main beam size). The error due to bad pointing was calculated using the interferometric data for $^{12}$CO(1–0) and the error pointing of each telescope [2 arcsec rms for the APEX and 3 arcsec rms for the data from Petitas & Wilson (2003)]. We studied the difference between the lines produced by varying the centre within the error in the pointing and found that this effect corresponds to additional 11 per cent for the 2 arcsec rms and 15 per cent for the 3 arcsec rms.

3.2 Local thermodynamic equilibrium and $X_{CO}$ conversion factor analysis

With the estimated intensities and ratios of the lines, we used two different methods to estimate the molecular gas physical properties in the inner kpc (21 arcsec) of NGC 1097: (i) the $X_{CO}$ conversion factor; and (ii) the local thermodynamic equilibrium (LTE) approximation. Although, none of these methods is fully realistic for our unresolved data, they are instructive for comparison with the estimations using a LVG approximation.

Using the $X_{CO}$ conversion factor and the line $^{12}$CO(1–0), we estimated the H$_2$ column density of the inner 21 arcsec. We used a value for $X_{CO}$ of $3 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Scoville et al. 1987; Solomon et al. 1987; also used by Hsieh et al. 2008) for an illustrative estimation of the molecular gas density. With our estimation of the integrated intensity of the line, we obtained a column density of $(2.7 \pm 0.3) \times 10^{22}$ cm$^{-2}$. This value is of the same order as the estimation made by Hsieh et al. (2008) at the radius of the starburst ring in this galaxy. However, using the conversion factor obtained from outside the Galactic plane $X_{CO} = 1.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Dame, Hartmann & Thaddeus 2001) implies a column density of $(1.6 \pm 0.2) \times 10^{22}$ cm$^{-2}$ and $X_{CO} = 0.4 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Martín et al. 2010) gives a column density of $(3.6 \pm 0.4) \times 10^{21}$ cm$^{-2}$.

We also analysed the emission assuming the LTE, by making use of a ‘Population Diagram’ (Goldsmith & Langer 1999), shown
in Fig. 2. The LTE approximation gives a linear relation between \( \ln(N_j/g_j) \) and \( E_j/k_B \) for a cloud, where \( N_j \) is the column density of the molecules with the energy state \( j(E_j) \) and \( g_j \) is the statistical weight for \( E_j \). The slope of this linear relation is inversely proportional to the kinetic temperature characteristic of the cloud. We estimated a typical kinetic temperature for \( ^{12}\text{CO} \) and \( ^{13}\text{CO} \) of about 10 K. In the case of an optically thick medium, this approximation only yields a lower limit for the column density. We derive a value that is indeed too low, which is due to the fact that in our LTE approximation we do not account for the optical thickness.

### 3.3 LVG analysis

The interferometric images of \( ^{12}\text{CO}(1–0) \) (Kohno et al. 2003) and \( ^{13}\text{CO}(2–1) \) (Hsieh et al. 2008) show that most of the CO emission comes from the very centre and the starburst nuclear ring of the galaxy. In reality, the connection points of the ring with the dust lanes of the primary bar present a clear increase in the emission. In the following sections, we analyse the molecular gas physical properties of these regions by performing a radiative transfer analysis of the single-dish data described in Section 2.

To improve the estimation of the parameters presented in the previous section, we modelled the ratios of the observed lines using a non-LTE radiative transfer code, \textsc{Radex} (van der Tak et al. 2007), available at http://www.strw.leidenuniv.nl/~moldata/radex.html. \textsc{Radex} assumes the LVG approximation and gives the expected line intensity of a molecular cloud with a characteristic kinetic temperature \( T_K \), molecular hydrogen density \( n(H_2) \), \( ^{12}\text{CO} \) column density \( \Sigma(^{12}\text{CO}) \) and linewidth \( \Delta v(^{12}\text{CO}) \).

We studied these properties using a \( \chi^2 \) minimization by comparing the observed line ratios with the ratios generated by \textsc{Radex}. We built a three-dimensional matrix made of different \( \chi^2 \) values created by changing the three principal input properties in the radiative transfer code and varied the inputs within the ranges 10–150 K (40 steps) for the kinetic temperature, \( 10^{10}–10^{16} \) cm\(^{-3} \) (50 steps) for the molecular hydrogen density and \( 10^{15}–10^{18} \) cm\(^{-2} \) (30 steps) for the \( ^{12}\text{CO} \) column density. We fixed the internal \( ^{12}\text{CO} \) linewidth to 1 km s\(^{-1} \) and the abundance ratio \( [^{12}\text{CO}] / [^{13}\text{CO}] \) to 40 (cf. 40 ± 10 found for the centre of active galaxies; Henkel et al. 1993; Maursberger & Henkel 1993; Henkel et al. 1998; Bayet et al. 2004; Israel 2009). We further confirm that changing the abundance ratios between 30–50 introduces only marginal changes in the final results.

After fixing the abundance ratio and the linewidth, there are only three free parameters (namely temperature, density and column density) in the scenario which depict the four observed ratios that we are analysing here. However, there are still several possible solutions from which we select the best alternative using the combination of two criteria: the optical depth should be in agreement with previous findings (e.g. \( < 10 \) as previously found by Petitpas & Wilson 2003) and minimizing the combination of individual \( \chi^2 \) for every ratio.

The errors were estimated using a bootstrap method and by looking at the fluctuation of each parameter around the \( \chi^2 \) minimum (see Fig. 3, where the red curves mark the 1σ \( \chi^2 \) confidence level contours).

![Figure 3](http://example.com/fig3.png)

**Figure 3.** The graphs on the top present the confidence levels of the \( \chi^2 \), assuming normally distributed data, around the parameters with minimum \( \chi^2 \). The minimum value is illustrated by the red star. The red curve marks the position of the 1σ \( \chi^2 \) confidence level. The graphs on the bottom show the upper limit optical depth distribution of the lines modelled by \textsc{Radex} (see Section 3.3 for details). The red curve marks where the \( \chi^2 \) confidence level is equal to 1σ and the black curve shows the \( \tau = 8 \) contour. The best physical parameters are \( T_K = 33^{+10}_{-15} \) K, \( n(H_2) = 10^{5.9\pm0.9} \) cm\(^{-3} \) and \( \Sigma(\text{CO}) = 10^{16.7\pm0.5} \) cm\(^{-2} \).
3.4 The inner 21 arcsec: one-component model

The circumnuclear 21 arcsec diameter hosts the active nucleus as well as the inner starburst ring with radius $\approx 10$ arcsec. Our single-dish observations are affected by the beam-dilution effect in the measured line strength, since the size of the beam is larger than the individual clouds, and the clumpiness of the clouds and the large beam size produce an unknown filling factor. However, using line ratios with an equal beam size, instead of the full line profile, and assuming that the emission of every transition comes from the same clouds, these problems are avoided (see also Petitpas & Wilson 2003; Israel 2009).

Applying the $\chi^2$ minimization method explained above, we generated the confidence levels of the $\chi^2$ around the optimal three physical parameters: temperature, density, and column density (Fig. 3). We estimated a kinetic temperature of $33^{+100}_{-45}$ K, a molecular hydrogen density of $10^{3.0\pm0.5}$ cm$^{-3}$ and a $^{12}$CO column density of $10^{16.5\pm0.8}$ cm$^{-2}$, imposing an upper limit for the optical depth of $\tau = 4.9$ (in agreement with Petitpas & Wilson 2003), and using an abundance ratio $[^{15}$CO$/[^{13}$CO] of 40 and an internal linewidth of 1 km s$^{-1}$. The upper limit of the optical depth means the biggest value estimated by Rades for all transitions. The temperature changes by 5\(\%\) and the molecular hydrogen density by less that a factor of 2 while changing the $[^{15}$CO$/[^{13}$CO] abundance between 30–50.

These estimations are more robust, fully consistent with the limits presented by Petitpas & Wilson (2003) and present an average density larger than $10^{8}$ cm$^{-3}$ as expected from the observation of HCN(1-0) in the nucleus by Kohno et al. (2003). We estimated the errors in the magnitudes by looking at 1\(\sigma\) confidence level and an upper limit of the optical depth $\tau < 8$.

Moreover, we obtained a $^{12}$CO column density of $4 \times 10^{16}$ cm$^{-2}$ for a linewidth of 1 km s$^{-1}$. If we assume a typical linewidth of 30 km s$^{-1}$ (Kohno, Kawabe & Vila-Vilaró 1999) and a $[^{12}$CO $]/[^{13}$CO] concentration ratio of $10^{11}$ (Wilson, Kohlls & Hüttemeister 2009), we obtain a H$_2$ column density of $1.2 \times 10^{22}$ cm$^{-2}$, which is also in agreement with the estimation made using the $X_{CO}$ conversion factor presented in Section 3.2. The kinetic temperature is in accordance with the value derived using the LTE approximation, but its uncertainty of 100 K shows a possible contribution of a warmer component.

3.5 Inner 21 arcsec: two-component model

The central 21 arcsec ($\sim 1$ kpc) of the galaxy hosts a multitude of molecular clouds with sizes of the order of tens of parsecs and very likely exhibiting differing physical conditions. Thus, the one-component model is not realistic to describe the entire region covered by the unresolved central beam of NGC 1097. We take a step further in an attempt to describe the typical physical properties of the cold interstellar gas using more than one component (cf. Israel 2009). We presumed the inner kpc to be formed by a cold (30 K) and a warm (90 K) component, and made a similar $\chi^2$-minimization study explained previously in this section by varying the H$_2$ densities, $^{12}$CO column densities and the fraction between the two components $F = [\text{cold component}] / [\text{warm + cold component}]$.

We changed the input variables within the ranges $\log_{10}(n(H_2)_{\text{box}}) = [3, 6]$ (cm$^{-3}$, 20 steps), $\log_{10}(n(^{12}$CO)$_{\text{box}}) = [1.5, 4.5]$ (cm$^{-2}$, 20 steps), $\log_{10}(\Sigma(^{12}$CO)) = [15, 18] (cm$^{-2}$, 14 steps) and $F = [0, 1]$ (8 steps). In the selection of the ranges for the densities, we imposed the cold component to be denser than the warm component.

We fixed the abundance ratio $[^{15}$CO$/[^{12}$CO] to 40 and the $^{12}$CO linewidth to 1 km s$^{-1}$, and imposed the same conditions for finding the minimum $\chi^2$ value as explained previously in this section: a low optical depth for the two components and a proper value for the $\chi^2$ of all individual pairs of line ratios. Our results are shown in Table 3 with a ratio $F = 0.85$. It is important to note here that the $\chi^2$ analysis has been carried out using different steps for the fitted parameters and different limits for the optical depth and $\chi^2$ of the individual ratios in order to constrain the confidence of the method. The results are correlated within the errors, making stronger their confidence.

4 EMISSION LINES AT DIFFERENT VELOCITY REGIONS

4.1 Dissecting the inner 21 arcsec

In this section, we use an innovative approach where we ‘de-confuse’ the single-dish data to be able to study ‘resolved’ emission lines for which no interferometric data have yet been obtained. We used the resolved interferometric intensity and kinematic maps from Kohno et al. (2003) to select five different regions along the starburst ring for a deeper analysis of their physical properties. Following the combination of two independent criteria, we selected different knots along the starburst ring to analyse the state of the molecular gas.

The regions were selected to have a $^{12}$CO(1-0) $S/N \geq 150$ and span a range of velocity greater than one frequency/velocity channel. These choices have been made to ensure that the region can be separated from other velocity channels in the unresolved single-dish data and has a $S/N$ high enough to return reliable measurements for the different transitions. Furthermore, all regions have mean line-of-sight velocities such that they can be separated from each other in the velocity channels of the single-dish data. Two regions are located on the intersection of the bar dust lanes with the ring (regions A and B), other two regions at 90 $'$ distance (in the upper and lower side of the ring, regions C and D) and a fifth region E in another maximum CO(1-0) emission between A and C and close to a connection point (see Fig. 4).

To avoid unnecessary complications regarding the exact shape of each star-forming knot, we opted to select a rectangular shape along an outer radius of 10.5 arcsec and an inner radius between 7–8 arcsec, given their full area fits inside our beam. A narrow velocity range is essential for us since we aim to examine the contribution of this selected region to the global line and it is imperative that the different regions have different velocities to distinguish them in the single-dish lines.

Once the regions were selected and their velocity ranges were established, we studied their contribution to the global unresolved single-dish emission line (see Fig. 5). We took the channels which corresponded to the velocity range of each region and generated the line ratios using only these channels. We estimated the ratio’s errors by adding the standard deviation of the channels to the errors.

| Table 3. Kinetic temperature $T_K$, column density $n(H_2)$, surface density $\Sigma(^{12}$CO) and optical depth $\tau$ from the one- and two-component models. |
|-----------------|-----------------|-----------------|
|                 | One component   | Two component   |
| $T_K$ (K)       | 35$^{+100}_{-15}$ | 30              |
| log$_{10}(n(H_2))$ (cm$^{-3}$) | 5.0$^{+1.0}_{-0.9}$ | 3.9$^{+2.1}_{-0.5}$ |
| log$_{10}(\Sigma(^{12}$CO)) (cm$^{-2}$) | 16.7$^{+0.3}_{-0.6}$ | 16.7$^{+0.3}_{-0.6}$ |
| $\tau(^{12}$CO) | <4.9            | <6.6            |

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Figure 4. The five regions along the inner starburst ring of NGC 1097 with the two bar–ring connection points marked as A and B. All regions are overplotted on the underlying $^{12}$CO(1–0) intensity map (left-hand panel). All regions were selected taking into account their distinct velocities and the S/N criterion as described in Section 4.1, and the full velocity window which contributes to the signal in the corresponding channel is marked in the $^{12}$CO(1–0) velocity field (right-hand panel). In the velocity field, each group of coloured squares indicate pixels with velocity inside the velocity range of each region.

Figure 5. The emission lines analysed in this paper (new APEX data, Kohno et al. 2003; Petitpas & Wilson 2003), showing the contribution to the lines of the different regions.

listed in Section 2. With this, we have introduced the error due to a possible bad selection of the velocity intervals.

Thus, for each region, we obtained four different line ratios (see Table 4). Looking at the ratios, it is possible to infer that the physical properties should be similar for every region, since the ratios are somewhat similar within the errors, but for the case of $^{13}$CO(3–2)/$^{12}$CO(3–2).

To ensure the physical properties along the ring, we analysed the ratios for each region, following the procedure described in Section 3.3. We realized the $\chi^2$-minimization study described above for every region (see Section 3.3), imposing again that the optical depth should not exceed 5. The results are shown in Table 4.

Moreover, we note that the results presented in Table 4 are not uniquely representative of the physical conditions of the regions from the star-forming ring only. To estimate the contribution from other parts which exhibit velocities which are in the range selected for each of the knots along the ring, we calculate the ratio of the $^{12}$CO(1–0) intensities from the full region inside the velocity range and that from the ring. We find that the contribution of the signal from the ring is at best 70 per cent of the pixels inside the chosen velocity range (though could be as low as 35 per cent). This fact confirms that single-dish data cannot be used to rigorously derive the physical properties of the ring only, but instead that of regions inside isovelocity contours. Nevertheless, one can assume that the region inside the ring (i.e. galactocentric radius < 8.5 arcsec) is much more homogeneous than the ring itself and the fact that we have derived comparable physical properties are indicative of a rather homogeneous ring in NGC 1097.

4.2 The star-forming knots along the ring

In star-forming rings, stars are expected to form from the accreted material because of the shocks and compressions during the accretion process (e.g. Elmegreen 1994) and these processes could arise randomly by gravitational instabilities without any specific order along the ring. In the case of NGC 1097, where the ring is postulated to be at the location of the ILR, such a scenario would naturally imply that the bulk of the compressive forces act on the regions where the ring meets the bar dust lanes and thus the bar may well trigger the star formation in the ring (cf. Knapen et al. 2006; Fathi et al. 2008) at the connection points and the star formation would thereafter successively migrate along the ring following the rotation period of $\approx 18$ Myr (cf. Böker et al. 2008). The $^{12}$CO(1–0) and $^{12}$CO(2–1) emission maps of the ring (Kohno et al. 2003; Hsieh et al. 2008) present clear peaks of the intensity in the regions around the dust lanes connecting points with the ring (A, B and E in Fig. 4) and hence may indicate stronger star formation on those spots. This could imply an increase in the molecular gas density with respect to the rest of the ring.

Our improved LVG analysis using five different regions at different velocities does not show significant differences between the
molecular gas densities, temperatures or column densities (see Table 4). It is possible that the measured similarity between the derived molecular gas densities could be due to a bad estimation of the contribution of the ring to the observed region. However, the region inside the ring (radius <8.5 arcsec) shows relatively small \(^{12}\)CO(1–0) intensity variation as well as small variations in the H\(z\) intensity as shown in high-resolution Hubble Space Telescope images presented in Fathi et al. (2006). It is thus likely that the star-forming gas inside the ring is rather homogeneously distributed; hence, its contribution to our derived physical properties along the different regions described in Section 4.1 is similar. Consequently, our derived values hint that the conditions of the molecular gas at the different regions along the ring are comparable.

These results are consistent with the recent far-infrared and submillimetre studies, from the Herschel Space Observatory, of the ring in NGC 1097 which showed no azimuthal age gradient (Sandstrom et al. 2010), accompanied by an increase in the ionized gas density over the full ring associated with the star formation activity (Beirão et al. 2010). Moreover, we compare the regions selected here with the resolved Very Large Array radio continuum maps (Beck et al. 2005, their fig. 14) and find that all star-forming knots exhibit radio emission, indicative of the ongoing star formation at comparable intensities.

The strong \(^{12}\)CO(1–0) and \(^{12}\)CO(2–1) emission observed with the interferometric data (Kohno et al. 2003 and Hsieh et al. 2008) on the connecting points may be due to particularly strong shocks, as predicted by the peak of the ratio [O\(\text{II}\)] \(63\ \mu\text{m}/[\text{C}\text{II}]\) 158 \(\mu\text{m}\) (Beirão et al. 2010) and not necessarily due to the triggered strong star formation.

## 5 MASS-INFLOW RATE ON TO THE SMBH

The fuelling of the active nucleus of NGC 1097 has been subject to much debate recently. Modelling the spectral energy distribution, Nemmen et al. (2006) estimated the mass-inflow rate of \(m_{\text{in}} = 6.4 \times 10^{-3} M_{\odot}\text{ yr}^{-1}\), with the Eddington accretion rate of \(M_{\text{Edd}} = 2.7 M_{\odot}\text{ yr}^{-1}\), for a 1.2 \(\times 10^8 M_{\odot}\) black hole. Recently, van de Ven & Fathi (2010) used two-dimensional spectra in the optical to kinematically derive the mass-inflow rate from ionized gas. These authors measured the inflow velocity from a kinematic analysis and the electron density from [S\(\text{II}\)] observations, consistent for the most inner part with Nemmen et al. (2006). Davies et al. (2009) estimated an upper limit 1.2 \(M_{\odot}\text{ yr}^{-1}\). These studies are based on simplifications of the inflow mechanism along the nuclear spiral arms and also on indirect measurements of the inflowing material by assuming that the hot ionized gas traces the underlying cold molecular gas.

We estimated the mass-inflow rate using our direct measurement of the molecular gas density, \(\rho_{\text{gas}}\), obtained for the central kpc of NGC 1097 (see Section 3.4). We combined it with the inflow velocity estimation from van de Ven & Fathi (2010) and their mass-inflow rate analysis:

\[
\dot{M} = m v_{\text{inflow}} \Delta \rho_{\text{gas}} \pi R^2 \frac{h}{R} \frac{1}{4 m}, \tag{1}
\]

where \(m\) is the number of arms, \(v_{\text{inflow}}\) is the inflow velocity, \(\Delta \rho_{\text{gas}}\) is the overdensity on the arms, \(R\) is the galactocentric radius and \(h\) is the disc scaleheight. We assumed a nuclear spiral arm overdensity of 10 per cent, that is, \(\Delta \rho_{\text{gas}} = 0.1 \rho_{\text{gas}}\) (e.g. Engelmaier & Shlosman 2000; Maciejewski 2004) and for comparison also measured the mass-inflow rate using the electron overdensity measured by van de Ven & Fathi (2010). We further compare the results by estimating the scaleheight \(h\), taking into account the thickness of the disc, and used the criterion of marginal stability \(Q_{\text{eff}} = 1\) (Roméo 1994), where

\[
Q_{\text{eff}} \sim Q(1 + 2\zeta); \quad \zeta = \frac{h_c^2}{2\pi G \Sigma_{\text{gas}}}, \quad Q = \frac{\kappa c_s}{\pi G \Sigma_{\text{gas}}}, \tag{2}
\]

where \(\kappa\) is the epicyclic frequency, \(c_s\) is the sound speed (we use \(c_s = 10\ \text{km s}^{-1}\) and \(\Sigma_{\text{gas}} \approx \rho_{\text{gas}}/h\) is the gas column density. We did not find a significant difference between this assumption and the marginally stable disc, and we attribute this to the fact that we are measuring the cold molecular gas which is thinner than its ionized counterpart, that is, the cold gas component has \(h/R < 1\). We obtained several measurements for the mass-inflow rate on to the SMBH in NGC 1097 as shown in Fig. 6.

Our measurement using the thick disc description is 0.11 \(M_{\odot}\text{ yr}^{-1}\) at 1 arcsec = 70 pc distance from the SMBH, which is the radius at which the line-of-sight velocities were reliably measured by van de Ven & Fathi (2010). This value is still in agreement with the accretion estimation for the transition between Sy1 and LINER galaxies (Ho 2005); however, it puts NGC 1097 on the more efficient end of the distribution of the transition objects. Our inflow rate at 70 pc is within the upper limit derived by Davies et al. (2009) and is one order of magnitude greater than the value derived by van de Ven & Fathi (2010). The difference with the latter work is driven by the fact that while our cold disc remains thin (\(h/R < 1\)), the ionized disc of van de Ven & Fathi (2010) thickens and to avoid this these authors applied an upper limit for \(h/R\), leading to a lowering of the mass-inflow rate (cf. equation (1)).
The ratio with the CO intensity yields the mass-inflow rate of the inner 400 parsec radius of NGC 1097. Combining the surface densities and the marginal stability criteria, over an area similar to the beam size. We translate this surface column density to the molecular hydrogen column density, dividing by a factor of 1.36 corresponding to the helium contribution to the gas.

We have the integrated velocity intensity for each beam (3 per cent for a beam size of 15 arcsec and 10 per cent for a beam size of 21 arcsec). More-
by episodic star formation in the ring connection points with the bar
dust lanes, the star-forming complexes could migrate along the ring
in a very short time. In such a case, the star-forming knots along
the ring are expected to exhibit similar properties, since they ‘mix’
very efficiently. This is further supported by the fact that the knots
coincide with knots of enhanced radio continuum emission (Beck
et al. 2005).

Making use of our new derivations of the cold gas densities, we
have been able to revise the mass-inflow rate on to the SMBH in
NGC 1097. We derived an inflow rate of $1.1 M_{\odot}$ yr$^{-1}$ for a thick
disc and concluded that accounting for the total interstellar medium
and applying a careful contribution of the disc thickness and corre-
responding stability criterion increases the inflow rate by a factor of
10. The critical value $0.01 M_{\text{Edd}}$ for the transition between LINER
and Sy1 galaxies was found by Ho (2005) with a distribution over
three orders of magnitude. Our new measurement of the accretion
rate on to the SMBH of NGC 1097 places this galaxy at the higher
end of this distribution, and combining our derived accretion rate
with the updated Eddington ratio presented in Eracleous, Hwang
& Flohic (2010), NGC 1097 is placed in the regime between the
advection-dominated mass accretion and accretion via a thin disc
structure (e.g. Narayan, Mahadevan & Quataert 1998).

We have moreover calculated the $X_{\text{CO}}$ conversion factor for the
centre of NGC 1097 using an independent estimation of the surface
density to the CO emission. We used the same analysis described in
van de Ven & Fathi (2010) from the kinematics of NGC 1097. We
obtained $X_{\text{CO}} = (2.8 \pm 0.5) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ at a radius of
10.5 arcsec and $X_{\text{CO}} = (5.0 \pm 0.5) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ at a radius of 7.5 arcsec. The surface density given by this ‘kinematical
method’ and that given by the $X_{\text{CO}}$ conversion factor are in agree-
ment, for example, CO(4–3), with the Atacama Large Millimetre
Array (ALMA) will help overcome most of the limitations that we
have faced in this work. The ALMA data will (i) give us the com-
plete description of the properties of star-forming knots in the ring;
(ii) allow us to calculate the exact mass-inflow rate for different
radii by resolving the density for different radii; and (iii) resolve the
unknown nature of the $X_{\text{CO}}$ conversion factor in the circumnuclear
kpc of this prototype LINER/Sy1 Galaxy.

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