The extended H$_i$ halo of NGC 4945 as seen by MeerKAT

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ABSTRACT

Observations of the neutral atomic hydrogen (H$_i$) in the nuclear starburst galaxy NGC 4945 with MeerKAT are presented. We find a large amount of halo gas, previously missed by H$_i$ observations, accounting for 6.8% of the total H$_i$ mass. This is most likely gas blown into the halo by star formation. Our maps go down to a 3σ column density level of 5 × 10$^{18}$ cm$^{-2}$. We model the H$_i$ distribution using tilted-ring fitting techniques and find a warp on the galaxy’s approaching and receding sides. The H$_i$ in the northern side of the galaxy appears to be suppressed. This may be the result of ionisation by the starburst activity in the galaxy, as suggested by a previous study. The origin of the warp is unclear but could be due to past interactions or ram pressure stripping. Broad, asymmetric H$_i$ absorption lines extending throughout the H$_i$ emission velocity channels are present towards the nuclear region of NGC 4945. Such broad lines suggest the existence of a nuclear ring moving at a high circular velocity. This is supported by the clear rotation patterns in the H$_i$ absorption velocity field. The asymmetry of the absorption spectra can be caused by outflows or inflows of gas in the nuclear region of NGC 4945. The continuum map shows small extensions on both sides of the galaxy’s major axis that might be signs of outflows resulting from the starburst activity.

Key words: instrumentation: interferometers – methods: data analysis – galaxies: spiral

1 INTRODUCTION

Starburst galaxies are characterised by their intense burst of star formation over a short period (Coziol 1996). Their star formation rates range from ∼ 10 $M_{⊙}$ yr$^{-1}$ to ∼ 1000 $M_{⊙}$ yr$^{-1}$. There are sub-classes of starburst galaxies; those with a vigorous nuclear star formation, e.g., NGC 4945, NGC 253, NGC 660, NGC 1068, NGC 1365, NGC 1808, NGC 3079 (Koribalski 1996; Emig et al. 2020) and those that have a more distributed star formation mode, e.g., NGC 4631 (Irwin et al. 2011, 2012). This paper focuses on the study of the edge-on
nuclear starburst galaxy NGC 4945. For simplicity, we will refer to it simply as a starburst galaxy throughout the paper. The high levels of star formation in the nuclear region of starburst galaxies are thought to be due to gas accretion onto the centre, induced by bars, galaxy interactions or past merging events (Ishizuki et al. 1990; Ott et al. 2001; Lucero et al. 2015). Starburst galaxies have stellar populations dominated by massive stars, which transfer a significant amount of energy into the interstellar medium and, as a result, shape the gas distribution and kinematics of the galaxies (Freyer et al. 2003; Zhang et al. 2018). Simulations show that star formation can drive the gas out of the disc plane, mostly as ionized gas. The gas eventually cools and rains back to the disc, fuelling future episodes of star formation. This so-called galactic fountain model (Shapiro & Field 1976) is consistent with observations of starburst galaxies. For example, extra-planar gas has been observed in the starburst galaxy NGC 4945 (Venturi et al. 2018) and its twin NGC 253 (Boomsma et al. 2005; Lucero et al. 2015), as well as the dwarf starburst galaxy M 82 (Martin et al. 2018). Edge-on galaxies offer a better way to study the vertical distribution of the gas compared to galaxies seen more face-on. For example, deep Westerbork Radio Telescope (WSRT) H$i$ observations of the edge-on galaxy NGC 891 by Oosterloo et al. (2007), labelled as a quiescent starburst galaxy by Temple et al. (2005), show large quantities of extra-planar gas, extending up to a vertical distance of 22 kpc. Thus, observations of the gas content of starburst galaxies are important in the studies of the mechanisms that initiate and regulate starburst activity.

The neutral atomic hydrogen gas (H$i$) remains the best tracer of the overall gas distribution and kinematics in galaxies. This is because H$i$ can be traced out to a considerable distance from the galactic centre. Previous H$i$ observations of nearby starburst galaxies have allowed the investigations of the possible triggering mechanisms of starburst. For example, the early H$i$ observations of M 82 revealed that its velocity field showed strong deviations from circular motions, suggesting possible interactions with M 81. Subsequent H$i$ observations show filamentary structures connecting M 81, M 82 and NGC 3077, forming what is called the M 81-triplet (Yun et al. 1994; de Blok et al. 2018; Sorgio et al. 2019). The interaction of M 82 with its neighbour is thought to have triggered its starburst activity (Mayya et al. 2006). H$i$ observations of NGC 253 by Lucero et al. (2015) unveiled extra-planar gas emission out to a projected distance of ~9 to ~10 kpc from the nucleus and up to 14 kpc at the edge of the disc. Extra-planar gas has also been found for other starburst galaxies such as NGC 3079, NGC 4945, NGC 891 (Swaters et al. 1997; Ott et al. 2001; Fraternali et al. 2001; Boomsma et al. 2005; Oosterloo et al. 2007; Gentile et al. 2013; Marasco et al. 2019). Extra-planar gas is also common in normal star-forming spiral galaxies. For example, The Hydrogen Accretion in LOcal GALaxieS survey (HALOGAS, Heald et al. 2011) found halo gas enclosing about 5–25% of the total H$i$ mass (Marasco et al. 2019), and moving slower than the gas in the disc of normal galaxies.

The amount of extra-planar H$i$ found in starburst galaxies by previous observations is within the range found for normal galaxies (Boomsma et al. 2005; Lucero et al. 2015). With the improved sensitivity of MeerKAT, we aim to get high-quality H$i$ imaging to trace possible halo gas that might have been missed by previous H$i$ observations. In addition, we would like to compare the amount and distribution of the extra-planar H$i$ we found for our starburst galaxy with those for normal galaxies. In this paper, we report high sensitivity H$i$ observations of the nuclear starburst galaxy NGC 4945 with MeerKAT. Our H$i$ map is about 2.5 times deeper in column density than previous ATCA mosaic imaging by LVHIS (Koribalski et al. 2018). NGC 4945 is a nearby edge-on starburst galaxy belonging to the Centaurus A group. The distance to NGC 4945 quoted in the literature varies between 3.8 to 8.1 Mpc (de Vaucouleurs 1964; Baan 1985; Bergman et al. 1992; Ott et al. 2001; Karachentsev et al. 2007; Mouled & Sakai 2008). Here we adopt a distance of 6.7 Mpc for easy comparison with the results of Ott et al. (2001) and other relevant studies. NGC 4945 is classified as a SB(s)cd galaxy (de Vaucouleurs et al. 1991). The central region of NGC 4945 harbours several physical processes. Apart from hosting a nuclear starburst, NGC 4945 is known to have a Seyfert 2 nuclei, which is thought to be responsible for some of its out-flowing gas (Done et al. 1996). Moreover, the nuclear region of NGC 4945 is among the richest sources of molecular lines, and therefore it has extensively been studied in the millimetre wavelengths (Dahlem et al. 1993; Henkel et al. 1994; Curran et al. 2001; Ott et al. 2001; Hitschfeld et al. 2008; Hagiwara et al. 2016; Henkel et al. 2018). Measurements of different molecular abundance ratios in NGC 4945 suggest that its starburst activity is possibly reaching an advanced evolutionary stage (Curran et al. 2001; Cunningham & Whiteoak 2005). Some authors classified NGC 4945 as a post-starburst galaxy (Koornneef 1993). However, this was not confirmed by subsequent studies. The H$i$ disc of NGC 4945 radially extends just a bit larger than the bright optical disc as shown by the ATCA map of Koribalski et al. (2018) and our MeerKAT data shown in this paper. This is peculiar for late-type spiral galaxies whose H$i$ disc usually extends well beyond the optical disc (Ott et al. 2001; Koribalski et al. 2018). Other starburst galaxies that share this peculiarity include NGC 253 (Koribalski et al. 2018) and NGC 1433 (Ryder et al. 1996).

In this paper, we show high sensitivity maps of the radio continuum emission and the H$i$ spectral line emission/absorption in NGC 4945 obtained with MeerKAT. Aided by the large field of view of MeerKAT, we obtained, for the first time, the most complete H$i$ map of NGC 4945 with only a single pointing. This allows us to trace potential star formation outflows much more easily (Lucero et al. 2015; Ryder et al. 1996).

2 OBSERVATIONS AND DATA REDUCTION

NGC 4945 was observed with MeerKAT during 24–26 of May 2019. The data was taken over two observing epochs using the L-band receiver, centred at 1284 MHz, with a bandwidth of 856 MHz divided into 4096 channels (44 km s$^{-1}$ in velocity resolution). The compact radio sources PKS 1934–63, PKS 0408–65, and J1331+3030 were used as the bandpass calibrators, and J1318–4620 as the gain calibrator. Each observing run starts and ends with the bandpass calibrator, which was tracked every two hours. The target and the gain calibrator were tracked one after the other. Thus, we spend 10 mins on bandpass every 2 hours, within which we cycle through 15 mins target exposure and 2 mins gain calibrator observation. This results in a total observing time of 15 hours 50 minutes, during which 12 hours 50 minutes were spent on the target.

The CARACal\footnote{https://github.com/caracal-pipeline/caracal} (Józsa et al. 2020) data-reduction pipeline was used to produce a spectral-line data cube and a continuum image
ready for scientific analysis. Based on Python/Stimela scripts, CARACal incorporates many tasks from standard data-reduction software, e.g., CASA (McMullin et al. 2007), MeqTrees (Noordam, J. E. & Smirnov, O. M. 2010), CubiCal (Kenyon et al. 2018), SoFiA (Serra et al. 2015), which can be run sequentially using a YAML (a human-readable data-serialization language) configuration file through which the users can control which tasks need to be run/turned off and in which order. CARACal can perform all the standard data-reduction steps of radio astronomical data, from flagging, calibration to imaging. CARACal is written in Python and uses container-based data processing technologies such as Singularity, Docker, uDocker or Podman, allowing it to run across different platforms. Although CARACal was initially developed to reduce data from MeerKAT, its scope has been broadened to allow data processing from any other radio telescopes. Examples of peer-reviewed papers using CARACal include Janjamasimanana et al. (2020), de Blok et al. (2020), Józsa et al. (2021).

We use a bandwidth of 30 MHz, centred around the H\textsubscript{i} line of NGC 4945. To produce the final data used in this analysis, first, radio frequency interference (RFI) were flagged using the AOFlagger (Offringa 2012). Then, cross-calibration was performed using the CASA task gaincal to solve for the time-dependent delays (K) and complex gains (G) of each antenna, and the bandpass task to obtain the bandpass (B) solutions. After that, the data were passed through the CARACal selfcal worker to perform self-calibration. For that, five successive WSClean (Offringa et al. 2014) imaging loops and phase-only gain corrections with CubiCal (Kenyon et al. 2018) were used. The clean mask threshold was iteratively lowered in each step until the continuum residual was noise-like. Finally, to produce the spectral line data cube, first, the continuum clean model produced in the self-calibration step was subtracted from the calibrated data. After that, the CASA task mstransform was used to fit the remaining continuum with a polynomial function of order one and subtract it from the data. The continuum subtracted data were then cleaned using WSClean in its multi-scale mode. A robust parameter of 0 was used, which resulted in a synthesised beam size of 7.5′′ × 6.4′′. The rms noise of the final data cube is 0.085 mJy beam\(^{-1}\), which is close to the expected theoretical noise of 0.070 mJy beam\(^{-1}\), calculated from the radiometer formula and using a penalty factor of 1.5 to account for robust weighting. We further smooth the data to a 60′′ circular beam with the MIRIAD (Sault et al. 1995) task CONVOL. The rms noise of the 60′′ cube is 0.20 mJy beam\(^{-1}\). Note that the detected halo gas reported in this paper is already clearly visible even at the highest spatial resolution (i.e., 7.5′′ × 6.4′′) as shown in the Appendix. One may think that smoothing the cube to a larger beam after cleaning could result in large-scale wings and ripples in the dirty psf mimicking halo gas. However, our use of a multi-scale cleaning, which uses different size scales, already addresses these issues. In addition, we have also used a mask produced by SoFiA during an initial imaging step to produce our final image. We show the low-resolution version in this paper to emphasise the halo gas and speed up the processing time for the 3D kinematic modelling. Thus, the results presented in the main section of the paper are those using the smoothed data cube unless stated otherwise in the paper. In addition, we made two versions of the radio continuum map of NGC 4945, one at a resolution of 17.6′′ × 15.8′′, and another one at a resolution of 7.3′′ × 6.2′′. This paper presents the continuum map at 17.6′′ × 15.8′′ unless otherwise stated.

3 RESULTS

3.1 \textit{H\textsubscript{i}} channel maps and global profile

We present the MeerKAT \textit{H\textsubscript{i}} channel maps of the starburst galaxy NGC 4945 in Fig. 1. They reveal previously unseen fluffly faint \textit{H\textsubscript{i}} emission surrounding and/or connected to the main disc of the galaxy. They are most clearly visible at channels \(V = (466, 510, 554, 598)\) km s\(^{-1}\) as indicated by the white arrows in the Figure. We are unsure about their exact origin due to the lack of velocity resolution. We could not model them properly and have excluded them in our modelling presented in Section 3.3. We will discuss its possible origin in Section 4. We present the global \textit{H\textsubscript{i}} profile of NGC 4945 in Fig. 2. The global profile is double-horned, typical of spiral galaxies with a flat rotation curve. In addition, it is asymmetric, with the approaching side having higher peak flux-density than the receding side. By fitting the profile using the busy function (BusyFit, Westmeier et al. 2014), we find a \(W_{20}\) (full width at 50% of the peak flux) of 359 km s\(^{-1}\), a \(W_{20}\) (full width at 20% of the peak flux) of 397 km s\(^{-1}\), and a systemic velocity of \(v_{\text{sys}} = 530\) km s\(^{-1}\). Note that the \(v_{\text{sys}}\) we use throughout the rest of the paper is the one we estimated from the tilted-ring modelling described in section 3.3. From the \textit{H\textsubscript{i}} intensity map we measure a total \textit{H\textsubscript{i}} flux of 509 Jy km s\(^{-1}\). Single dish observations using the Parkes radio telescope resulted in a measured flux of 319 Jy km s\(^{-1}\), \(v_{\text{sys}} = 563\) km s\(^{-1}\), and \(W_{50} = 361\) km s\(^{-1}\) (HIPASS, Koribalski et al. 2004). The ATCA mosaics imaging by Koribalski et al. (2018) yielded a total flux of 405.3 Jy km s\(^{-1}\). Thus, we detect 37% and 20% more flux than the HIPASS and the LVHIS surveys, respectively. Using our adopted distance of 6.7 Mpc, we measured a total \textit{H\textsubscript{i}} mass of \(5.4 \times 10^{8} M_{\odot}\). Recall that here only a single pointing was required to map the extended \textit{H\textsubscript{i}} disc of NGC 4945, which is thanks to the large primary beam of MeerKAT. Due to the strong \textit{H\textsubscript{i}} absorption present towards the nuclear region of the galaxy, the estimated total mass represents the \textit{H\textsubscript{i}} mass seen in emission but not the total \textit{H\textsubscript{i}} mass.

3.2 \textit{H\textsubscript{i}} moment maps

To get a map of the integrated \textit{H\textsubscript{i}} intensity and velocity field of NGC 4945, we calculate the zeroth- and the first-moment of its channel maps and global profile. We present the MeerKAT \textit{H\textsubscript{i}} channel maps of the starburst galaxy NGC 4945 in Fig. 1. They reveal previously unseen fluffly faint \textit{H\textsubscript{i}} emission surrounding and/or connected to the main disc of the galaxy. They are most clearly visible at channels \(V = (466, 510, 554, 598)\) km s\(^{-1}\) as indicated by the white arrows in the Figure. We are unsure about their exact origin due to the lack of velocity resolution. We could not model them properly and have excluded them in our modelling presented in Section 3.3. We will discuss its possible origin in Section 4. We present the global \textit{H\textsubscript{i}} profile of NGC 4945 in Fig. 2. The global profile is double-horned, typical of spiral galaxies with a flat rotation curve. In addition, it is asymmetric, with the approaching side having higher peak flux-density than the receding side. By fitting the profile using the busy function (BusyFit, Westmeier et al. 2014), we find a \(W_{20}\) (full width at 50% of the peak flux) of 359 km s\(^{-1}\), a \(W_{20}\) (full width at 20% of the peak flux) of 397 km s\(^{-1}\), and a systemic velocity of \(v_{\text{sys}} = 530\) km s\(^{-1}\). Note that the \(v_{\text{sys}}\) we use throughout the rest of the paper is the one we estimated from the tilted-ring modelling described in section 3.3. From the \textit{H\textsubscript{i}} intensity map we measure a total \textit{H\textsubscript{i}} flux of 509 Jy km s\(^{-1}\). Single dish observations using the Parkes radio telescope resulted in a measured flux of 319 Jy km s\(^{-1}\), \(v_{\text{sys}} = 563\) km s\(^{-1}\), and \(W_{50} = 361\) km s\(^{-1}\) (HIPASS, Koribalski et al. 2004). The ATCA mosaics imaging by Koribalski et al. (2018) yielded a total flux of 405.3 Jy km s\(^{-1}\). Thus, we detect 37% and 20% more flux than the HIPASS and the LVHIS surveys, respectively. Using our adopted distance of 6.7 Mpc, we measured a total \textit{H\textsubscript{i}} mass of \(5.4 \times 10^{8} M_{\odot}\). Recall that here only a single pointing was required to map the extended \textit{H\textsubscript{i}} disc of NGC 4945, which is thanks to the large primary beam of MeerKAT. Due to the strong \textit{H\textsubscript{i}} absorption present towards the nuclear region of the galaxy, the estimated total mass represents the \textit{H\textsubscript{i}} mass seen in emission but not the total \textit{H\textsubscript{i}} mass.

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The observations by the LVHIS survey (Koribalski et al. 2018) provide the most sensitive \textit{H\textsubscript{i}} maps of NGC 4945 in the literature. On the receding side, the radial extent of the moment zero map of our

\footnote{https://github.com/ratt-ru/Stimela/wiki}
MeerKAT H\textsubscript{i} observation is similar to the extent found by LVHIS as it also ends at the edge of the optical disc as shown in Fig. 3. However, on the approaching side, our map radially extends slightly further than that of LVHIS. In addition, we find significantly more gas in the lower left quadrant of the galaxy than what was detected by the LVHIS. This is due to our improved sensitivity, going down to a 3\textsigma\ column density level of $5 \times 10^{18}$ cm\textsuperscript{-2} at a 44 km s\textsuperscript{-1} velocity resolution and a 60\textarcmin beam, compared to $1.2 \times 10^{19}$ cm\textsuperscript{-2} for LVHIS.

The finger-like structures seen on both sides of the major axis of NGC 4945 were already apparent on the LVHIS map, though they are more clearly visible here. The area where H\textsubscript{i} absorption occurs appear as blanked pixels in Fig. 3. There is a central concentration of high-density gas extending symmetrically with respect to the minor axis towards each side of the galaxy. The disc velocity field shows the regular spider pattern, which indicates a rotationally-supported system. There are kinks in the iso-velocity contours, which have usually been attributed to non-circular motions caused by bars, spiral arms or star formation. In addition, irregular patterns are seen in the South-Eastern side where the faint extended emission is detected. Finally, the iso-velocity contours appear to be twisted on the approaching and the receding sides, indicating a warp-like morphology.
The velocity field indicates a clear solid-body rotation pattern, very if the broad lines were caused by gas moving at random velocity. (1993), there would be no systematic shift in velocity with position (2001). Thus, the broad H\textsc{i} asymmetry value is always greater than 1, independent of whether

\begin{equation}
N_{\text{HI}} = 1.82243 \times 10^{19} \frac{T_s}{F_{\text{HI, abs}}} \frac{f}{F_{\text{HI, cont}}} \Delta v,
\end{equation}

where \(T_s\) is the spin temperature of hydrogen atoms in K, \(F_{\text{HI, abs}}\) is the flux from the H\textsc{i} absorption lines in Jy beam\(^{-1}\), \(F_{\text{HI, cont}}\) is the flux from the 21-cm radio continuum in Jy beam\(^{-1}\), \(f\) is the covering factor, and \(\Delta v\) is the channel width in km s\(^{-1}\). We find \(N_{\text{HI}}\) = 1.7 \times 10\(^{19}\) - 1.3 \times 10\(^{20}\) [Ts/f cm\(^{-2}\)]. The spin temperature is a poorly constrained parameter and depends on a lot of excitation mechanisms such as the cosmic microwave background radiation (CMB), collisional excitation, and Ly\(\alpha\) radiation (Field 1959). The column density of the H\textsc{i} emission in the central region of NGC 4945 is well above the threshold value for cold neutral medium formation (CNM), \(N_{\text{HI}}\gtrsim 2 \times 10^{20}\) cm\(^{-2}\) (Kanekar et al. 2011). Thus we expect the H\textsc{i} in the central region of NGC 4945 to be predominantly in the cold phase with Ts \lesssim 500 K (Kanekar et al. 2011). This is supported by the presence of molecular gas in NGC 4945 as reported by Ott et al. (2001) and the high rate of nuclear star formation, indicating an enhanced atomic-to-molecular conversion process.

### 3.3 Kinematic modelling

To model the H\textsc{i} gas distribution and kinematics in NGC 4945, we use the 3D tilted ring fitting software FAT (Kamphuis et al. 2015) and TiRiFiC (Józsa 2007). FAT is built upon TiRiFiC but was designed to be run in a fully automated manner. FAT and TiRiFiC model a galaxy as a set of concentric rings with kinematic and orientation parameters that can either be varied or held fixed with radius. Each ring is characterised by its centre position, inclination angle with respect to the line of sight, position angle of the receding major axis, systemic velocity, rotation velocity, velocity dispersion, vertical thickness, and surface brightness distribution. The disc can be segmented and fitted independently, allowing the user to e.g., fit the approaching and the receding halves independently. TiRiFiC can be used to model non-axisymmetric features and large-scale motions such as those induced by the presence of bars. This can be achieved by including harmonic distortions in velocity and/or surface brightness distribution while modelling.

#### 3.3.1 Modelling strategy

To model NGC 4945, first, we make a base model with FAT. Then, we use the output model of FAT as input for TiRiFiC to refine the model and identify features not captured by FAT. We start with the simplest possible model, i.e., a model with the geometric parameters, systemic velocity, and velocity dispersion held fixed with radius, but allowing for the surface brightness and the rotation velocity to vary as a function of radius. We visually compare the resulting model with the data and add/modify one or more parameters if the simpler model does not adequately describe the data. As briefly mentioned before, we excluded the faint emission in the fitting as we failed to properly model it due to our coarse velocity resolution of 44 km s\(^{-1}\). We will discuss more the properties of the anomalous
gas in Section 3.4. Thus, in addition to applying a mask based on the 75'' data as described in the previous section, we create an elliptical region surrounding the main disc of the galaxy and use the MIRIAD task IMMMASK to mask out areas outside the ellipse. We put zeros in the areas that have been masked out. The masked data cube is then fed into TiRiFiC for the modelling. Note that due to the presence of the central absorption, which has been masked out, the fitting in the central part (about an arcminute in radius) is uncertain. Thus we refrain from doing mass modelling.

3.3.2 Model parameters

Our final best-fitting model is a model where we fit the approaching and receding sides separately as described below.

- The following parameters have been kept constant with radius:
  (a) centre position: XPOS, YPOS, XPOS_2, YPOS_2
  (b) systemic velocity: VSYS, VSYS_2
  (c) global dispersion: CONDISP (this does not vary with radius by default, and should not be confused with the SDIS parameter which can be varied with radius)
  (d) disc thickness: Z0, Z0_2

- The following parameters have been allowed to vary with radius:
  (a) rotation velocity: VROT, VROT_2
  (b) surface brightness: SBR, SBR_2
  (c) amplitude of harmonic distortions in surface brightness (first and second order): SM1A, SM1A_2; SM2A, SM2A_2
  (d) phase of harmonic distortions in surface brightness (first and second order): SM1P, SM1P_2; SM2P, SM2P_2
  (e) inclination: INCL, INCL_2
  (f) position angle: PA, PA_2

We show the parameters that are kept constant with radius in Table 1. The ones that vary with radius are shown in Fig. 6 and Table 2.

General properties:

- We derive a flat rotation curve, typical of spiral galaxies. A fit to
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Figure 5. Left: velocity field of the H\textsc{i} absorption in the central region of NGC 4945, using the data cube at 7.5\arcsec\ × 6.4\arcsec\ resolution. The contour levels are (480, 525, 570, 615, 660, 705) km s\(^{-1}\). Right: column density map of the H\textsc{i} absorption in the central region of NGC 4945, using the data cube at 7.5\arcsec\ × 6.4\arcsec\ resolution. The contour levels are 0.1 to 1.2 in step of 0.1 in units of \(10^{20} \text{[Ts/f]} \text{cm}^{-2}\). The black ellipses in each panel show the beam.

Table 1. Tilted-ring parameters not varying with radius.

| NGC 4945 TiRiFiC model parameters that are constant with radius | Value |
|---------------------------------------------------------------|-------|
| Model centre (J2000) XPOS | 13.0\(^{h}\)05.0\(^{m}\)28.0\(^{s}\) ± 0.0\(^{s}\) |
| Systemic Velocity VSYS | 565 ± 6 km s\(^{-1}\) |
| Thickness Z0 | 42.6\(^{\prime\prime}\) ± 3.0\(^{\prime\prime}\) |
| Dispersion CONDISP | 23.0 ± 1.5 km s\(^{-1}\) |

the following function (Boissier et al. 2003; Leroy et al. 2008)

\[
  v_{\text{rot}}(r) = v_{\text{flat}} \left[ 1 - \exp \left( 1 - \frac{r}{l_{\text{flat}}} \right) \right],
\]

(3)

gives the numbers quoted in Table 3, where \(v_{\text{rot}}(r)\) is the rotation curve, \(v_{\text{flat}}\) is the rotation velocity at the flat part of the rotation curve, \(l_{\text{flat}}\) is the length scale over which \(v_{\text{rot}}\) approaches \(v_{\text{flat}}\) (Leroy et al. 2008).

- The position angle and inclination clearly indicate an outer warp in the approaching and the receding sides.
- The surface brightness profile decreases toward the centre due to the presence of the absorption. It appears to be disturbed (irregular), most likely due to a bar.

Properties of the kinematic model: The approaching side shows a steeper velocity gradient than the receding side. This is already apparent in the velocity field. However, their maximum rotation velocities agree within the uncertainties. In addition, both sides have an outer warp. Moreover, there are differences in the radial variations of the surface brightness distribution. The receding side appears to be brighter in the inner discs and fainter in the outer discs compared to the approaching side. The amplitude and the phase of the first-order harmonic distortions in surface brightness for the two sides are similar, though.

3.3.3 TiRiFiC model vs data

We compare the H\textsc{i} channel maps from the TiRiFiC model data cube with the H\textsc{i} channel maps from the observed data cube in Fig. 7. Overall, the agreement is good, except close to the systemic velocity. This is expected due to the absorption in the centre and the effects of radial/streaming motions possibly related to a bar, which are not included in the modelling. We compare the H\textsc{i} moment maps from the TiRiFiC model with the H\textsc{i} moment maps from the observations in Fig. 8. The model recovers the overall gas distributions and kinematics. Local deviations exist, though. We also show the residual H\textsc{i} moment maps obtained by subtracting the model from the data in Fig. 8. The residual velocity field has a mean value of \(-1.4 \text{ km s}^{-1}\), an rms of 11.1 \text{ km s}^{-1}, and a median absolute deviation of 9.5 \text{ km s}^{-1}. The largest deviation is \(-92.1 \text{ km s}^{-1}\), however; there are only 5 pixels that have deviations above the channel spacing. We show the H\textsc{i} position-velocity diagrams from the TiRiFiC model and the observed data cubes in Fig. 9. Overall, they agree with each other. However, the position-velocity diagram from slice C shows the largest discrepancy between the model and the data. As mentioned before, this is mostly due to the central absorption that has been blanked and set to zero fluxes before performing the fit.
Due to our limited velocity resolution, the individual H\textsc{i} profiles of NGC 4945 could not be decomposed into multiple Gaussian components as was done for NGC 253 by Lucero et al. (2015). To summarize, they visually inspected each PV slice aligned along the galaxy’s major axis to spot any kinematically anomalous gas component. In addition, they interactively fitted three Gaussians to all the line profiles making each PV slice. In our case, even using two Gaussians to fit the profiles failed in most cases. Thus, to separate the anomalous H\textsc{i} from the galaxy’s disc, we use the kinematic model data cube derived by TIRIFIC as outlined above to mask the main disc of the galaxy and isolate the kinematically anomalous gas. We show the structure of the halo gas in Fig 11. We tried to derive the rotation curve of the anomalous gas separately but failed to obtain reliable kinematics.

We found an H\textsc{i} mass of $3.7 \times 10^9 \, M_\odot$, which accounts for 6.8% of the total H\textsc{i} mass of the galaxy. This is almost twice as large as the fraction of the anomalous gas found in NGC 253 (Lucero et al. 2015). However, despite being a starburst galaxy, the fraction of the anomalous component we find for NGC 4945 is still well within the range expected for normal disc galaxies. Marasco et al. (2019) performed a Bayesian Markov chain Monte Carlo (MCMC) kinematic fit to 11 normal disc galaxies from the HALOGAS survey and found that about 5% to 25% of the H\textsc{i} gas in their sample reside in the halo of the galaxies. Here, we expected to see more extra-planar H\textsc{i} in NGC 4945 than in normal galaxies. This is because, as reported in the literature (e.g., Strickland & Stevens 2000; Heckman et al. 2000), the brief burst of intense star formation leads to the existence of superwind and multiple episodes of type II supernova explosions in starburst galaxies. The combined effects of these mechanisms are expected to drive more gas in the halo than seen in normal galaxies. However, as demonstrated by Heckman et al. (2000); Heckman (2003), starburst-driven superwind could accelerate a cloud of gas to a velocity larger than the velocity needed to escape the gravitational force.
potential of the host galaxy ($v_{esc}$). This would result in a fraction of gas being driven to the surrounding intergalactic medium instead of ending up in the halo. Heckman et al. (2000); Heckman (2003) demonstrated that the superwind’s energy loss due to radiative cooling in starburst galaxies is not strong enough to halt this process. This may be why being a starburst galaxy does not simply translate to having more extra-planar H i than normal galaxies. The escaped gas could be in the ionized form or a tenuous gas, escaping the detection limit of the current emission line surveys.

It is not uncommon to find more halo gas on one side than on the other side of galaxies, and this is true for both normal and starburst galaxies. If we cut NGC 4945 into two halves, 20% of the anomalous gas resides in the northern side of the minor axis, whereas 79% of the halo gas resides in the southern side. Similarly, 42.4% of the halo gas is located above the major axis, and 57.6% below the major axis of the galaxy. We have assumed a position angle of 45° for the calculation.

We highlight the velocity field of the anomalous component in Figure 12. The iso-velocity contours of the halo gas are irregular, and in general, do not follow the overall rotation pattern of the main disc. If the gas is of a galactic fountain origin, which is plausible as NGC 4945 is a starburst galaxy, the irregularity of the velocity pattern of the halo gas indicates unsettled H i that will be accreted back onto the main disc of the galaxy at a later stage. An outer disc star formation could also cause such an irregularity. This can be investigated further using deeper Hα imaging. However, the star formation in NGC 4945 is so far known to be confined in its central part.

3.5 Radio continuum map

Distribution and total flux: To produce the 20-cm radio continuum map of NGC 4945, we selected a 100 MHz chunk of the raw data around the central emission of NGC 4945 to be reduced by CARACal. WSClean was used in its multi-scale mode to account for the different size scales in the continuum map of NGC 4945. We let WSClean select the relevant scales automatically. Using a robust parameter of 0 and a Gaussian taper of FWHM = 15", the final beam size is 17.6" × 15.8". The rms of the final residual continuum image is 0.053 mJy beam⁻¹, whereas the rms of the continuum image is 0.06 mJy beam⁻¹. We show an overlay of the radio continuum map of NGC 4945 onto a DSS B-band optical image in Fig. 13. The central continuum peaks at RA (J2000) = 13° 05' 27.4" and DEC (J2000) = −49° 28' 5", which agrees well with the centre position found by Whiteoak & Bunton (1985); Elmouttie et al. (1997); Ott et al. (2001). The emission extends over 11.3" × 4.5" at a position angle of 45° at a level of 1 mJy beam⁻¹. See the Appendix for an illustration on how these numbers were estimated. Using ATCA, Ott et al. (2001) measured an extent 11.6" × 3.3" at a major axis position angle of 45°. Thus, we derive a similar major-axis extent as Ott et al. (2001) but a slightly larger minor axis extent.

The continuum emission associated with the optical disc of the galaxy is shown in Fig. 13. The continuum is very extended and follows the optical disc of the galaxy, though its radial extent is much less than that of the optical disc. It is characterised by a bright central core with a peak flux density of 3.74 Jy beam⁻¹. In addition, there is a moderately bright, localised continuum emission along the major axis of the galaxy. Finally, a small extension of weak emission (which looks like an asymmetric double horned profile) is seen on the South-East side of the galaxy. Symmetric to that (with respect to the major axis), there seems to be a (finger-like)
**Figure 7.** Comparison between the observed and the model H\textsubscript{i} data cubes of NGC 4945. Here, only the gas from the main disc of NGC 4945 is shown since we could not fit the gas in the halo as mentioned in the text. Blue: H\textsubscript{i} channel maps of observed data cube; deep pink: channel maps of TiRiFiC model data cubes. The contour levels are 0.0072, 0.0240, 0.0480, and 0.1200 Jy beam\textsuperscript{−1}. The black circles at the bottom left corner of each panel show the size of the beam (FWHM = 60′).
Figure 8. Comparison between the NGC 4945 H\textsubscript{i} moment maps from the observed and the model data cubes. Only the gas from the main disc of the galaxy is shown as we failed to model the gas in the halo of NGC 4945. Top left: comparison between the observed H\textsubscript{i} surface density map and the TiRiFiC model surface density map. Arrows A, B, C, and D show slices from which the position-velocity diagrams shown in Fig. 9 and Fig. 10 are taken. The intersection between arrow A and arrow C represents the kinematic centre derived by TiRiFiC. The blue contours show the observed H\textsubscript{i} surface density. The deep pink contours represent the surface density map from the TiRiFiC model data cube. The contour levels are 1, 5, 15, 25, and 55 M\textsubscript{\odot} pc\textsuperscript{-2}. Top right: first moment maps; the blue contours represent the observed velocity field, the deep pink contours show the model velocity field. The contour levels are $V_{sys} \pm 175$ km s\textsuperscript{-1} in steps of 35 km s\textsuperscript{-1} where $V_{sys} = 565$ km s\textsuperscript{-1}. The residuals are shown in the bottom panels of the Figure. Bottom left: the difference between the observed H\textsubscript{i} surface density and the model H\textsubscript{i} surface density. Bottom right: the difference between the observed velocity field and the model velocity field. The circles at the lower left corners of each plot represent the size of the beam (FWHM = 60\arcsec).
extension, although it is very weak. These may be signatures of outflows caused by star formation activity. We show a plot of the central continuum emission in Fig. 13. Our observation does not resolve the very compact nuclear core of NGC 4945. Ott et al. (2001) found a source size of $7.6'' \times 3.4''$. However, to get the central flux distribution at our resolution, we show a plot of the flux density as a function of position along a slice taken at a major axis position angle of 45° in Fig. 13. The profile has a bright narrow core and faint broad wings. We fit a double Gaussian function to the profile and derived a dispersion of $\sigma = 15.4''$. As shown in Fig. 13, most of the emission in the core is contained within a diameter of twice this value, about $31''$ (1 kpc at 6.7 Mpc).

To calculate the total continuum flux, first, we blank all continuum emission not associated with the galaxy using the MIRIAD task IMMASK. After that, we sum all the remaining non-blanked pixels and convert the unit from Jy beam$^{-1}$ to Jy. We derive a total flux density of 6.2 Jy, of which 90% resides within a radius of 332'' (10.8 kpc). Thus, we recover ~26% more flux than Ott et al. (2001). A plot of the continuum map at the highest resolution ($7.2'' \times 6.3''$) is shown in the Appendix.

**Star formation**: The radio continuum emission at 1.4 GHz can be used to trace recent star formation since it is dominated by synchrotron radiation from supernovae remnants and thermal emission from H\textsc{ii} regions (Liu et al. 2015). To convert the 21 cm continuum to a star formation rate (SFR), we first convert the continuum flux to luminosity using the following relation from Yun et al. (2001); Martinsson et al. (2016):

$$\log L_{1.4\text{GHz}}[\text{W Hz}^{-1}] = 20.08 + 2 \log D[\text{Mpc}] + \log S_{1.4\text{GHz}}[\text{Jy}],$$

(4)

where $D$ is the distance in Mpc, $L_{1.4\text{GHz}}$ is the radio continuum luminosity in W Hz$^{-1}$, and $S_{1.4\text{GHz}}$ is the total flux density in Jy. We derive $L_{1.4\text{GHz}} = 3.3 \times 10^{22}$ WHz$^{-1}$. The radio continuum luminosity is known to correlate with far-infrared (FIR) luminosity, indicating a strong correlation between star formation and cosmic ray production (Yun et al. 2001, and references therein). Yun et al. (2001) analysed the FIR-radio continuum luminosity of 1809 IRAS 2 Jy sam-

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**Figure 9.** MeerKAT H\textsc{i} position-velocity diagrams from the model and the observed data cubes of NGC 4945 taken along slices A, B, C, and D as shown in Fig. 8. Here also we only show the gas in the main disc of the galaxy since we could not model the gas in the halo as mentioned in the text. Blue contours: observed data. Pink contours: the TiRiFiC model. The contour levels are (0.00072, 0.01200, 0.02400, 0.04800, 0.07200) Jy beam$^{-1}$. The elongated ellipses at the lower left corners of the plots shows the size of the beam (FWHM = 60'', along the x-axis) and the channel spacing (along the y-axis).
Figure 10. MeerKAT H\textsc{i} position-velocity diagrams of NGC 4945 taken along slices A, B, C, and D as shown in Fig. 8. Blue solid contours: H\textsc{i} emission; the contour levels are (2.5, 6, 14, 24, 100) \times \text{rms}, where rms is equal to 0.2 mJy beam\(^{-1}\). The circle symbols at the upper left panel show the TiRIFIC model rotation curve. Red dashed contours: H\textsc{i} absorption; the contour levels are (-14.0, -10.0, -6.0, -2.0, -0.8) mJy beam\(^{-1}\). The elongated ellipses at the lower left corners of the plots show the size of the beam FWHM = 60″ (along the x-axis) and the channel spacing (along the y-axis).

...and found the following best-fitting correlation:

\[
\log L_{\text{1.4GHz}} = (0.99 \pm 0.01) \log(L_{\text{opt/min}}/L_\odot) + (12.07 \pm 0.08) \quad (5)
\]

NGC 4945 has a nuclear FIR luminosity of \(4 \times 10^{10}\) \(L_\odot\). Using the above correlation, this corresponds to a 1.4 GHz luminosity of \(L_{\text{1.4GHz}} = 3.7 \times 10^{22}\) [W Hz\(^{-1}\)], which agrees with our observed value of \(L_{\text{1.4GHz}} = 3.3 \times 10^{22}\) [W Hz\(^{-1}\)]. We convert \(L_{\text{1.4GHz}}\) to SFR using the radio flux calibration of Bell (2003) (see also Liu et al. 2015) given by:

\[
\text{SFR}_{\text{RC}}[M_\odot\text{yr}^{-1}] = \begin{cases} 
5.52 \times 10^{-22}L_{\text{1.4GHz}} & \text{if } L_{\text{1.4GHz}} > L_C \\
5.52 \times 10^{-22} & \text{if } L_{\text{1.4GHz}} \leq L_C
\end{cases} 
\]

(6)

where SFR\text{RC} is the radio continuum SFR in \(M_\odot\text{yr}^{-1}\), and \(L_C = 6.4 \times 10^{23}\) W Hz\(^{-1}\) is the luminosity of a \(\sim L_\star\) galaxy. Since \(L_{\text{1.4GHz}} \leq 10^{23}\) for NGC 4945, the bulk of its radio continuum luminosity is expected to come from star formation rather than dominated by radio AGN (Yun et al. 2001). We derive a star formation rate of SFR\text{RC} = 18.4 \(M_\odot\text{yr}^{-1}\), 75% of which comes from the core having a diameter of 1 kpc (defined previously as the area containing most of the bright continuum emission). This value is on the low-end of the range observed in starburst galaxies (10-100 \(M_\odot\)).

4 DISCUSSION

This observation has changed our view of NGC 4945. We have found halo gas around almost the whole disc of the galaxies, not captured by previous H\textsc{i} observations. For future high spectral resolution observations of this galaxy, it would be possible to do the interactive profile fitting techniques done by Lucero et al. (2015) to separate the anomalous components in the galaxy and study the kinematics of the halo gas in detail. In this study, we have used the kinematic model of the galaxy to isolate the anomalous gas. Halo gas is found in virtually all sides of NGC 4945, with more H\textsc{i} located in
Figure 11. MeerKAT H\textsubscript{i} channel maps of the nearby starburst galaxy NGC 4945 showing the location of the anomalous gas (red contours) and the gas in the main disc of the galaxy (blue contours). The contour levels range from $3 \times$ rms to $20 \times$ rms in step of $7 \times$ rms and $20 \times$ rms to $400 \times$ rms in step of $20 \times$ rms where rms is 0.20 mJy beam$^{-1}$. The black circles shown at the bottom left corner of each panel show the beam (FWHM = 60\arcsec).
Figure 12. Top left: Moment-0 map of the main disc of NGC 4945. Top right: moment-zero map of the anomalous gas in NGC 4945. Bottom left: velocity field (moment-1) of the main disc of NGC 4945. Bottom right: velocity field of the anomalous gas in NGC 4945. The contour levels are 385 km s\(^{-1}\) to 745 km s\(^{-1}\) in step of 30 km s\(^{-1}\). The red crosses show the kinematic centre derived from TiRiFiC. The circles at the bottom left corner of each plot show the beam (FWHM = 60\arcsec).

the lower-left quadrant of the galaxy. Halo gas with asymmetric distribution has previously been found for NGC 253. While Boomsma et al. (2005) reported that the extra-planar gas in NGC 253 is only found in one side of the galaxy, the more sensitive map by Lucero et al. (2015) showed that the halo gas is also found in the southern part of the galaxy. The distribution is still clearly asymmetric, with the northern side having more anomalous H\(_i\) than the south side. For the starburst galaxy NGC 253, it was shown that the gas in the halo of NGC 253 has similar kinematics to the gas in the disc but is trailing by 10–20 km s\(^{-1}\) (Lucero et al. 2015). Future high-resolution studies of NGC 4945 can confirm if this is also the case for NGC 4945.

Many scenarios are proposed in the literature regarding the origin of gas in the halo of galaxies. These include the interaction of galaxies with a nearby companion or the environment, pristine gas from the cosmic web accreted onto the galaxies, gas being blown out of the disc into the halo by expanding superbubbles created by supernovae and stellar winds (Sanchez Almeida et al. 2014; Fraternali & Binney 2006; Marasco et al. 2019). NGC 4945 belongs to the Centaurus A group, and thus interaction with the intra-group medium may have played a role in forming its halo gas. The likelihood of the halo gas being from the cosmic web is low given the column density level at which we are detecting it. Accretion from the cosmic web is expected to happen at a lower column density level than we are probing. Thus, although we were unable to model the kinematics of the halo gas and compare to simulations, at least part of the halo gas we see here is likely due to outflows driven by the central starburst of the galaxy as seen in NGC 1808 and NGC 253 (Koribalski et al. 1993; Lucero et al. 2015).
The rotation curve of NGC 4945 resembles the overall spiral galaxy populations, most of which are characterised by a steep solid-body inner rotation curve and then flattens out to the outermost observed radius. There are exceptional cases where rotation curves are declining, such as that of NGC 253 (Hlavacek-Larrondo et al. 2011; Lucero et al. 2015), see also the cases for 22 nearby spiral galaxies compiled from the literature by Zobnina & Zasov (2020). We did not find a clear signature of a declining rotation curve for NGC 4945. As explained in Zobnina & Zasov (2020), cares need to be taken when interpreting a declining rotation curve since it does not necessarily indicate the edge of the dark matter halo.

We have fit the receding and the approaching sides of the galaxy separately to derive the rotation curve of NGC 4945. We have found that both sides have an outer warp. The warp on the receding side is more clearly visible in the models and the observed velocity field. The intensity distribution in the receding side appears to be suppressed since it extends just as much as the optical disc. This type of halo asymmetry has been found for NGC 253 (Boomsma et al.

Figure 13. Top left: MeerKAT radio continuum contour map of NGC 4945 (red contours) overlaid onto a DSS2 B-band optical image (grayscale). The contour levels are 0.00011 Jy beam$^{-1}$ to 3.8 Jy beam$^{-1}$ in step of 0.002 Jy beam$^{-1}$. Top right: continuum map of NGC 4945; the contour levels are 0.00011 Jy beam$^{-1}$ to 3.8 Jy beam$^{-1}$ in step of 0.002 Jy beam$^{-1}$. The red ellipse at the bottom left corner shows the beam (FWHM = 17.6″). The white arrow, taken at a position angle of 45°, shows the slice from which the profile at the bottom left of the Figure was taken. The white circle shows the diameter of the core measured by fitting the profile at the bottom left of the Figure with a Gaussian function. The diameter of the core is 31″. Bottom left: the central region of the continuum emission in NGC 4945. The contour levels go from 0.015 Jy beam$^{-1}$ to 3.72 Jy beam$^{-1}$ in step of 0.1 mJy beam$^{-1}$. The red ellipse at the bottom left corner shows the beam (FWHM = 17.6″). Bottom right: flux density as a function of position along the slice shown as the white arrow at the top right panel of the Figure, plotted in log-scale to highlight the two discs components. The blue line shows a double Gaussian fit to the profile. The shaded area shows a 2-σ width, where σ is the dispersion of the (fitted Gaussian) core component. The value of σ represents the diameter of the core of the disc shown by the white circle at the top right panel of the Figure. BMAJ represents the major axis of the beam.
They suggested that such a lack of H\textsuperscript{i} might be caused by ionization resulting from the galaxy’s starburst activity. For this to occur, though, the outer layer of the gas needs to be warped, which is the case for NGC 4945. Tidal interactions and ram pressure stripping are among the mechanisms that can cause H\textsuperscript{i} deficiency. Perhaps the warp in the receding side is related to this H\textsuperscript{i} suppression. However, it is worth noting that H\textsuperscript{i} deficient galaxies are not necessarily warped. The origin of a warp is still a subject of intense investigation in the literature (Sánchez-Salcedo et al. 2006; Poggio et al. 2020). Re-observation of this galaxy at higher velocity resolution will enable us to do proper modelling of the kinematics of the halo gas and investigate its possible origin based on existing models.

5 SUMMARY

We have presented MeerKAT H\textsuperscript{i} maps of the starburst galaxy NGC 4945, revealing for the first time the presence of faint H\textsuperscript{i} emission in its outskirts. The halo gas accounts for about 6.8\% of the galaxy’s total mass. This is thanks to the sensitivity of MeerKAT, enabling us to go down to a 3\sigma column density level of $5 \times 10^{18}$ cm$^{-2}$. Despite being a starburst galaxy and the improved sensitivity, the amount of the halo gas in NGC 4945 is within the range found for normal star-forming galaxies. This could indicate that there might be gas expelled from the galaxy into the intergalactic medium due to a starburst-driven supernovae (Strickland & Stevens 2000; Heckman et al. 2000). In addition, the halo gas does not seem to follow the kinematics of the disc (such as the trailing gas in NGC 891 or NGC 253), this could be another indication that there might be gas escaping the galaxy. After isolating the area of genuine emission, we derived a total H\textsuperscript{i} flux density of 509 Jy km s$^{-1}$, which is about 20\% higher than the flux density derived by Koribalski et al. (2018) using ATCA mosaic imaging. We have modelled the H\textsuperscript{i} emission through 3D tilted-ring modelling techniques using the TiRiFiC and FAT software (Józsa 2007; Kamphuis et al. 2015). The halo gas does not follow the regular kinematics of the main disc of the galaxy, and our attempt to fit it with TiRiFiC failed. Therefore, we have only made the kinematic modelling of the main disc of the galaxy. The modelling indicates the presence of a warp on the approaching and the receding sides of the galaxy. We derive a flat rotation curve with $v_{flat} = 176$ km s$^{-1}$ for the approaching side and $v_{flat} = 188$ km s$^{-1}$ for the receding side, in agreement with Kamphuis et al. (2015). Due to our coarse velocity resolution, only bright H\textsuperscript{i} emission were modelled here. Strong H\textsuperscript{i} absorption seen throughout the entire velocity range seen in H\textsuperscript{i} emission, is present towards the nucleus region of NGC 4945. The absorption lines appear to be broad and asymmetric, indicating the presence of a fast rotating ring and outflowing gas from the nuclei. The existence of a fast rotating ring is further supported by the clear rotation pattern in the absorption velocity field of NGC 4945. This fast rotation can be caused by the interaction of the surrounding neutral gas with the AGN at the centre of NGC 4945. A similar case has been found for NG 1808 by Dahlem et al. (1993). We have also presented a map of the radio continuum emission, most of which is associated with the bright optical disc of NGC 4945. The continuum emission is very extended and characterised by a bright central core with a diameter of about 0.6 kpc. The continuum flux suggests that NGC 4945 is forming stars at a global rate of $18.4 \ M_{\odot} yr^{-1}$, 75\% of which resides within a core radius of 1 kpc.

6 DATA AVAILABILITY

The data from this study are available upon request to the corresponding author, Roger Ianjamasimanana.

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In this Appendix, we show additional figures that complement the main section of the paper. The channel maps of NGC 4945 from the high-resolution data cube (7.5″ × 6.4″) is shown in Fig. A1. As mentioned previously, even at this resolution, the fluffy faint H I emission is already visible. The top left panel of Fig. A2, illustrates how we determine the extent of the H I disc as explained in Section 3.2 of the paper. Similarly, the top right panel of Fig. A2 shows an illustration of the estimation of the extent of the continuum map as mentioned in Section 3.5. To show the size of the continuum map relative to the size of the H I disc of NGC 4945, we overlay the continuum map on top of its H I surface density map. Finally, a high resolution version of the continuum map, i.e., at a resolution of 7.3″ × 6.2″ is shown at the bottom right of Fig. A2.
Figure A1. MeerKAT H\textsc{i} channel maps of NGC 4945 at a resolution of 7.5′′ × 6.4′′. The size of the beam is represented by the small dots at the bottom left corner of each panel.
Figure A2. Top left: H\textsubscript{I} surface density map of NGC 4945, arrows and dashed lines indicate the extent of the H\textsubscript{I} disc. The beam is shown by the black circle at the bottom left corner of the plot (FWHM = 60\arcsec). Top right: continuum map of NGC 4945, arrows and dashed lines indicate the extent of the continuum emission. The beam is shown by the black ellipse at the bottom left corner of the plot (FWHM\textsubscript{BMAJ} × FWHM\textsubscript{BMIN} = 17.6\arcsec × 15.8\arcsec). Bottom left: H\textsubscript{I} surface density map (coloured image) and the continuum map of NGC 4945 (black contours). The contour levels range from 0.0001 Jy beam\textsuperscript{-1} to 3 Jy beam\textsuperscript{-1} in step of 0.0015 Jy beam\textsuperscript{-1}. The black circle at the bottom left corner of the plot shows the beam (FWHM = 60\arcsec). Bottom right: the radio continuum map of the galaxy at a resolution of 7.3\arcsec × 6.2\arcsec. The beam is shown at the bottom left corner of the plot but is very small so it is not visible.