MIGHTEE-H I: the baryonic Tully–Fisher relation over the last billion years

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ABSTRACT

Using a sample of 67 galaxies from the MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey Early Science data, we study the H I-based baryonic Tully–Fisher relation (bTFr), covering a period of ~1 billion years (0 ≤ z ≤ 0.081). We consider the bTFr based on two different rotational velocity measures: the width of the global H I profile and V out, measured as the outermost rotational velocity from the resolved H I rotation curves. Both relations exhibit very low intrinsic scatter orthogonal to the best-fitting relation (σ⊥ = 0.07 ± 0.01), comparable to the SPARC sample at z ≈ 0. The slopes of the relations are similar and consistent with the z ≈ 0 studies (3.66 +0.39 −0.35 for W20 and 3.47 +0.37 −0.30 for V out). We find no evidence that the bTFr has evolved over the last billion years, and all galaxies in our sample are consistent with the same relation independent of redshift and the rotational velocity measure. Our results set-up a reference for all future studies of the H I-based bTFr as a function of redshift that will be conducted with the ongoing deep SKA pathfinders surveys.

Key words: Galaxies: evolution – Galaxies: kinematics and dynamics – Galaxies: spiral – dark matter.

I INTRODUCTION

The Tully–Fisher relation (TFr; Tully & Fisher 1977) is among the most fundamental dynamical scaling relations for spiral galaxies. It links the luminosity of a spiral galaxy to its rotational velocity through a very tight correlation. It was first used as a redshift independent tool to measure distances to galaxies, with the aim to measure the peculiar velocities and reconstruct local galaxy flows (e.g. Courtois et al. 2012; Tully et al. 2013, 2014, 2019; Dupuy et al. 2021). Since then, it has been extensively studied in the field of galaxy formation and evolution. It has been shown to hold for rotating galaxies of all morphological types (Chung et al. 2002; Courteau et al. 2003; den Heijer et al. 2015; Karachentsev, Kaisina & Kashibadze Nasonova 2017), in different environments (Willick 1999; Abril-Mégaroj et al. 2021), and over a large wavelength range from far-ultraviolet to near-infrared (NIR; Verheijen 2001; Ponomareva et al. 2017). Consequently, it has become a major tool with which to test galaxy formation and evolution models by examining their ability to reproduce the statistical properties of the TFr (slope, scatter, and zero-point).
The nature of the TFr is considered to be understood as the relation between two fundamental properties of spiral galaxies: their baryonic content, characterized by the luminosity, and the total dynamical mass, characterized by the rotational velocity. The luminosity traces the stellar mass of a galaxy, which is the reason why the infrared TFr has been the preferred choice for distance measurement, since the infrared is emitted predominantly from the old stellar population responsible for the bulk of the stellar mass (Sorce et al. 2013). The stellar mass, in turn, is a good proxy for the total baryonic mass. However, this is a reasonable assumption only for galaxies with rotational velocities $V \geq 100$ km s$^{-1}$. The lower velocity regime is populated by the gas-rich dwarf galaxies whose mass is dominated by cold gas (H I) rather than stars (McGaugh et al. 2000). Thus, inclusion of the cold gas mass resulted in the most fundamental form of the TFr: the baryonic Tully–Fisher relation (bTFr), the tight linear relation that spans ~5 dex in baryonic mass (McGaugh 2012; Lelli, McGaugh & Schombert 2016b; Lelli et al. 2019).

At $z \simeq 0$, the bTFr has been extensively studied for various galaxy sample, and has been the focus for testing different methods to evaluate the stellar mass and the rotational velocity of galaxies. The largest study to date is based on the SPARC (Spitzer Photometry & Accurate Rotation Curves) data base, which consists of 175 spiral galaxies with high-quality H I rotation curves (Lelli, McGaugh & Schombert 2016a). The importance of the resolved H I rotation curves for the bTFr studies has been extensively discussed in the literature (Verheijen 2001; Noordermeer et al. 2007; Lelli et al. 2016b; Ponomareva et al. 2017, 2018). Lelli et al. (2019) analysed the SPARC sample based on different velocity definitions, such as $W_50$ – the most commonly used rotational velocity measure derived from the integrated H I line profile, $V_{\text{flat}}$ – velocity measured at the flat part of the extended H I rotation curve, and $V_{\text{max}}$ – the maximum rotational velocity measured from the H I rotation curve. They found that the use of $V_{\text{flat}}$ yields the tightest bTFr with the steepest slope. These results agree with previous studies, which were based on much smaller samples (Verheijen 2001; Ponomareva et al. 2018), as well as with the recent studies based on simulations (Glownacki, Elson & Davé 2020). The results of the SPARC study provide important constraints on theories of galaxy formation and evolution: (1) the intrinsic scatter of the bTFr at $z \simeq 0$ is below the lowest value expected in $\Lambda$CDM cosmology (Dutton 2012); (2) the bTFr slope, when based on $V_{\text{flat}}$, must be in the range of 3.5–4, which is higher than the slope predicted by the basic $\Lambda$CDM models (McGaugh 2012); (3) the bTFr residuals do not correlate with galaxy size or surface brightness, contrary to the expectations from galaxy formation and evolution models (Desmond & Wechsler 2015); (4) Iorio et al. (2017) showed that there is no evidence for curvature at the low-mass end of the bTFr, despite the predictions by some semi-analytical galaxy formation models (Trujillo-Gomez et al. 2011; Desmond 2012). Moreover, Mancera Piña et al. (2019, 2020) have recently discovered that ultra-diffuse galaxies seem to be the only known population of galaxies which lies off the bTFr. This result challenges our current understanding of the feedback processes in dwarf galaxies.

To date, H I remains difficult to detect in emission beyond $z \simeq 0$, particularly for radio interferometers that are needed to provide spatially resolved H I kinematics. Therefore, other kinematic tracers of galaxies have been used to study the potential evolution of the bTFr with redshift. Topal et al. (2018) used carbon monoxide (CO) and found no bTFr evolution over the redshift range 0.05 $\leq z \leq$ 0.3. UBler et al. (2017) and Tiley et al. (2016, 2019) used optical kinematic tracers such as He emission line and found conflicting results at $z \approx 1$. The use of these kinematic tracers, however, has various drawbacks. First, both CO and optical emission lines have compact distributions and may not fully probe the dark matter (DM) halo potential, unlike H I, which extends far beyond the optical radius (Frank et al. 2016). Secondly, it is extremely challenging to compare the results at higher redshift to those at $z = 0$. For example, Tiley et al. (2019) showed that observational data quality can strongly bias the statistical properties of the measured TFr. This is especially important when comparing data that are not produced and analysed homogeneously. Ideally, one would need to compare the statistical properties of the bTFr at different redshifts using a blind, volume-limited survey of galaxies, selected in the same way.

The predictions from cosmological simulations and semi-analytical models of galaxy formation regarding the evolution of the bTFr are also limited. A recent study by Glownacki, Elson & Davé (2021) aimed to provide predictions for future H I surveys using the state-of-the-art cosmological simulation SIMBA (Davé et al. 2019) and found a clear evolution of the best-fitting linear parameters of the bTFr over the redshift range $z = 0 \rightarrow 1$, which can be mostly explained by the differences in the merger histories of the DM haloes.

Fortunately, the forthcoming H I surveys with the SKA pathfinder telescopes, such as Looking At the Distant Universe with the MeerKAT Array (LADA; Blyth et al. 2016) and the Deep Investigation of Neutral Gas Origins (Meyer 2009), together with existing surveys such as COSMOS H I Large Extragalactic Survey (Hess et al. 2019) and Blind Ultradeep H I Environmental Survey (Gogate et al. 2020), have the potential to systematically study H I in galaxies over a large range of redshifts. Another such survey is the MeerKAT International GigaHertz Tiered Extragalactic Exploration (MIGHTEE), one of the first deep, blind, medium-wide interferometric surveys for H I ever undertaken (Jarvis et al. 2016). It will detect more than 1000 galaxies in H I up to $z = 0.6$, thus allowing the systematic study of the evolution of the neutral gas content of galaxies over the past 5 billion years in different environments (Rancho et al. 2021) using direct detections and statistical stacking methods (Maddox et al. 2021; Pan et al. 2020, 2021).

In this work, we use the MIGHTEE Early Science data to perform, for the first time, a homogeneous study of the H I-based bTFr over the last billion years ($0 \leq z \leq 0.081$). Furthermore, we consider the bTFr based on two velocity measures: $W_50$ from the corrected width of the global H I profile, and $V_{\text{flat}}$, the rotational velocity measured at the outermost point of the resolved H I rotation curves. This allows us to study how the statistical properties of the bTFr change with redshift and with different definitions of the rotational velocity. Moreover, this is the first study which tests a completely automated version of 3D Barolo (Di Teodorico & Fraternali 2015) at higher redshift, software that was developed to derive H I rotation curves for the marginally resolved galaxies, in preparation for the new generation of large H I surveys.

This paper is organized as follows. Section 2 describes the MIGHTEE Survey and the Early Science data. Section 3 describes the baryonic mass measurements. Section 4 describes different velocity measurements. Section 5 discusses the results. Summary and conclusions are presented in Section 6.

## 2 MIGHTEE SURVEY

The MIGHTEE is a survey of four well-known deep, extragalactic fields currently being observed by MeerKAT, the SKA precursor radio interferometer located in South Africa (Jonas 2009). MeerKAT consists of 64 offset Gregorian dishes (13.5 m diameter main reflector and 3.8 m sub-reflector), and equipped with three receivers: UHF band (580 $< v < 1015$ MHz), L band (900 $< v < 1670$ MHz), and S band (1750 $< v < 3500$ MHz). The MeerKAT data are

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The continuum subtraction was done in both the visibilities and the bTFr (Ponomareva et al. 2018). It has been found to have a negligible effect on the statistical properties of the bTFr over the last billion years (Arnett 2013), they assume that galaxies follow the known functional form of the relation and a galaxy sample obeys a TFr with normal scatter, which might not be the case for a...  

### 3.2 H I mass

The total H I mass of each galaxy was calculated using

\[ \frac{M_{\text{HI}}}{M_\odot} = \frac{2.356 \times 10^5}{1 + z} \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{S}{\text{Jy km s}^{-1}} \right), \]

where \( D_L \) is the cosmological luminosity distance to the source, \( z \) is the redshift, and \( S \) is the integrated HI flux density, calculated from the moment-0 maps, as described in Meyer et al. (2017). Moment-0 maps were constructed for each galaxy individually as follows: first, the cubelets (cut-out from the original data cube centred on each detection) were smoothed to a circular beam of 20 arcsec \( \times \) 20 arcsec and clipped at 3\( \sigma \) threshold (where \( \sigma \) was obtained by measuring the noise over an emission-free region of the cubelet and calculating the standard deviation). The resulting mask was applied to the original resolution cubelet, thus allowing to take into account low column density diffuse H I emission. The moment-0 maps were constructed using the resulting masked cubelet. Then, every moment-0 map was examined by eye, and emission from the galaxy was isolated by masking out the noise peaks and negative flux values if any were present. To calculate the error on the integrated flux \( S \), we projected the source mask, used to construct the moment-0 map, to four emission free regions around the detection. We then measured the signal in each of the four regions and defined the uncertainty in the integrated flux of a galaxy as the mean rms scatter of the four flux measurements in the projected masks (Ramatsoku et al. 2016). As a result, the typical uncertainty on the H I mass varies from \(~\pm~\) 5 per cent for the high-mass galaxies to \(~\pm~\) 20 per cent for the lowest mass objects (\( M_{\text{HI}} \leq 10^8 M_\odot \)).

### 4 ROTATIONAL VELOCITIES

#### 4.1 Inclinations

The observed rotational velocity of a galaxy can be converted to an intrinsic velocity by taking into proper account the geometry of the source. Thus, any rotational velocity measure should be corrected for the inclination effect. For face-on discs, inclination corrections become very large due to the \( \sin(i) \) dependence. Even though there are proposed methods to estimate the statistical properties of the bTFr with no prior knowledge of the inclination (Obreschkow & Meyer 2013), they assume that galaxies follow the known functional form of the relation and a galaxy sample obeys a TFr with normal scatter, which might not be the case for a \( z > 0 \) study.

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1 http://casa.nrao.edu
Usually inclinations are measured using infrared photometry due to low extinction in the infrared bands. However, infrared bands trace older stellar populations that do not reside in the thin disc. A parameter that accounts for the thickness of a galactic disc \((q_0)\) is then used in addition to the axial ratio to measure the inclination (Mihalas & Binney 1981). To date, there is no agreement on the best value for \(q_0\). Some studies argue that it depends on the morphology of a galaxy and should vary (Giovanelli et al. 1997), while Tully et al. (2009) suggest that \(q_0\) should be fixed for all galaxies to avoid systematic uncertainties.

Conveniently, in addition to the stellar disc, also the \(H_1\) discs can be used to measure the inclination angles. In general, the \(H_1\) disc is much thinner than the stellar disc and its intrinsic thickness can be neglected (Verheijen & Sancisi 2001). However, due to disc flaring the \(H_1\) disc can become significantly thicker in the outer parts (Bacchini et al. 2019). We tested a thicker disc by setting \(q_0 = 0.2\), but found consistent results. Therefore, in what follows we assume an infinitely thin \(H_1\) disc for simplicity and for fair comparison with the measurements from \(^{3D}\) Barolo (see Section 4.3.1).

We measure inclination angles \((i_{H1})\) of our sample galaxies using \(H_1\) moment-0 maps as

\[
\cos^2(i_{H1}) = \frac{b^2 - a^2}{a^2 - c^2},
\]

where \(b\) and \(a\) are the minor and major axis of the \(H_1\) moment-0 map, measured by fitting an ellipse to the outermost reliable contour equal equal to \(1\ M_\odot \ PC^{-2}\), \(\theta_y\) and \(\theta_x\) are the sizes of the synthesized beam, used to correct for the beam smearing effect, which can make galaxies look rounder if they are not well resolved (Verheijen & Sancisi 2001). We assign a conservative error on the disc ellipticity of \(\sim 10\) per cent to account for the resolution and disc flaring effects, which results in the mean uncertainty of the \(i_{H1}\) of \(\sim 5\%\).

### 4.2 Line width measurement

Global \(H_1\) line profiles not only hold information about the amount of \(H_1\) gas in galaxies, but also about its kinematics. Usually, the line width for the bTFr studies is measured at 50 per cent of the peak flux density of the global \(H_1\) line profile \((W_{50})\) and, if corrected for instrumental broadening and random motions, gives a good representation of the maximum rotational velocity measured from a spatially resolved rotation curve: \(2V_{\text{max}} = W_{50}/\sin(i); \text{see fig. 6 in} \) Ponomareva, Verheijen & Bosma (2016).

For this study, we measure \(W_{50}\) for each galaxy by fitting the Busy function (BF; Westmeier et al. 2013), using multinest to explore the posterior distribution (Feroz & Hobson 2008; Feroz, Hobson & Bridges 2009).

The BF is defined as

\[
B(x) = \frac{a}{\xi^4} \{ \text{erf}(b_1[W + x - x_0]) + 1 \} \times \{ \text{erf}(b_2[W + x - x_0]) + 1 \} \times [c(x - x_p)^n + 1],
\]

where \(\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)dt\) is the Gaussian error function, \(a\) is the total amplitude scaling factor, \(b_1\) and \(b_2\) describe the steepness of the line flanks, \(W\) is the half-width of the \(H_1\) global profile, \(x_0\) and \(x_p\) are the offsets for the error functions and the polynomial, \(c\) is the scaling factor of polynomial trough, and \(n\) is the order of the polynomial.

The fit was performed with PYMULTINEST and uses the default initial parameters, such as tolerance = 0.5 and live points = 1000 (Buchner et al. 2014). The prior distributions of each parameter of the BF were set in the following ranges: \(a: U \in [0, 1]\), \(b_1: U \in [0, 1]\), \(b_2: U \in [0, 1]\), \(W: \log_{10} [-9, -7]\), \(c: \log_{10} [10^{-7}, 10^{-1}]\), \(n: U \in [2, 8]\), where \(U\) stands for the uniform range and log for logarithmic. Full details of the line-profile fitting will be presented in Mulaudzi et al. (in preparation). Fig. 1 illustrates an example of the fit for one of the sample galaxies.

The resulting \(W_{50}\) values were corrected for instrumental broadening and turbulent motions following the standard prescriptions (Verheijen & Sancisi 2001). Specifically, the instrumental broadening correction for our data is \(\sim 26\ km\ s^{-1}\), while \(5\ km\ s^{-1}\) was adopted as a standard correction for the turbulent motions when \(W_{50}\) is matched to \(V_{\text{max}}\) (Ponomareva et al. 2016).

The posterior distributions sampled by PYMULTINEST provide the typical error associated with \(W_{50}\) to be \(\sim 10\ km\ s^{-1}\). We combine this error in quadrature with a systematic uncertainty of 10 per cent of the line width to account for the masking applied prior to the fit, which is not fully accounted for in the fitting process.

### 4.3 3D kinematic modelling

Though \(W_{50}\) can provide a reliable estimate of the rotational velocity of a galaxy, its measurement is dominated by the high-density gas that tends to reside in the central regions of a galaxy. The kinematics of this gas may not be representative of the full potential of the system and \(W_{50}\) may differ from the velocities measured in the outer parts of spatially resolved rotation curves (Verheijen 2001; Ponomareva et al. 2016; Lelli et al. 2019). Therefore, to be able to study the bTFr in detail and compare to the existing studies at \(z = 0\) accurate 3D kinematic modelling is required.

Kinematic modelling has always been a complex procedure. The so-called tilted-ring modelling technique (Rogstad, Lockhart & Wright 1974) originally developed to fit the 2D velocity fields of spiral galaxies, required \(H_1\) observations to have very high spatial and velocity resolution, coupled with high signal-to-noise ratio (SNR) to derive a good-quality rotation curve. However, with new observational facilities and in preparation for the modern \(H_1\) surveys, new techniques and software have been developed that allow high quality kinematic modelling, even for marginally resolved galaxies, exploiting the full 3D parameter space of the data cubes (e.g. \(^{3D}\) Barolo, Di Teodoro & Fraternali 2015, TiRiFiC, Józsa et al. 2007).

Nowadays, kinematic modelling software is able to constrain the dynamics of the gas when a galaxy is resolved with only three resolution elements across its major axis and the SNR is larger than two (Di Teodoro & Fraternali 2015). Moreover, differently...
from the past, when a set of initial estimates for the galaxy main parameters (such as systemic velocity, position of the centre of a galaxy, position and inclination angles) was required to derive a rotation curve, state-of-the-art kinematic modelling software is able to perform a fit completely blind.

For our study, we use the latest fully automated version of 3D Barolo (1.6.1), a tool for fitting 3D tilted-ring models to emission-line data cubes (Di Teodoro & Fraternali 2015).

4.3.1 The sample and results

We construct our initial bTFr kinematic sample as follows. First, we use the tight relation between the H I mass and H I diameter (Wang et al. 2016) to define the radial extent of each galaxy,3 and retain those galaxies that have a size of at least with three resolution elements (see Table 1 for the beam sizes). We then select galaxies with corrected $W_{50} > 44$ km s$^{-1}$ since we are limited by the velocity resolution of the data. Finally, we select galaxies with $i_{H I} > 20$ deg because geometric corrections to the rotational velocities are large and uncertain for the less inclined galaxies$^3$ (Verheijen 2001; Ponomareva et al. 2016; Lelli et al. 2019). Consequently, our initial bTFr sample consists of 93 galaxies, which is $\sim 40$ per cent of the entire sample of the MIGHTEE-H I Early Science Data.

We conduct the first completely blind run of 3D Barolo on our initial sample, requesting two points of rotation curve per synthesized beam. In practice, the first run of 3D Barolo finds a galaxy in the cubelet and estimates its radial extent, centre, and systemic velocity. These parameters are then kept fixed, while rotation velocity, position and inclination angles, and velocity dispersion are fitted. While 3D Barolo performs well in recovering various parameters of galaxies, including the position angle of each source, inclination angles have been proven to remain a challenge. Fig. 2(a) shows the comparison between inclination angles obtained from 3D Barolo’s blind run and the H I inclinations measured from H I moment-0 maps (Section 4.3.1). While the majority of inclinations are within $10^\circ$ of $i_{H I}$, a clear trend is visible: 3D Barolo tends to overestimate inclinations for low values of $i_{H I}$ and underestimate them at higher inclinations. Following this, we perform a second run of the 3D Barolo modelling, but this time we use the $i_{H I}$ values as initial estimate and keep them unconstrained during the fit. In this case, 3D Barolo recovers the initial inclination values within $\sim 5^\circ$ range, see Fig. 2(b). Therefore, the inclination of a galaxy remains the main caveat for the blind kinematic modelling for low-resolution data, and should be measured carefully in advance either from the H I moment-0 maps, or from ancillary photometry. We note that the inclination measured from our optical ancillary data and the H I data are consistent.

We then perform an assessment of the resulting models by visually inspecting the data, model and residuals, as well as the resulting rotation curves projected on the position–velocity diagrams (see figs 5 and 6 in Maddox et al. 2021). Only 67 of 93 galaxies pass our visual assessment criteria.5 They form the final bTFr sample that covers the 0.006 < $z$ < 0.081 redshift range.6

Resolved rotation curves represent the velocity of a galaxy as a function of radius. Normally, the velocities for the bTFr are measured either at the peak of the rotation curve ($V_{\text{max}}$) or as an average velocity of its flat part ($V_{\text{flat}}$). As stated previously, the use of the latter provides the tightest bTFR, since it is likely to better trace the DM halo potential (Ponomareva et al. 2018; Lelli et al. 2019). However, since our sample galaxies cover a wide range of radial extents ($\sim 30$ beams for large nearby spirals down to three beams for the sources at the highest redshift), we base our analysis on the rotational velocity measured at the outermost H I radius $V_{\text{out}} = V(R_{\text{out}}$; Papastergis & Shankar 2016). This is not only to simplify the analysis, but also to have a homogeneous measurement of the rotational velocity for all galaxies in the sample, given that the definition of the flat part of the rotation curve consisting of few points is very ambiguous (Lelli et al. 2016b). Therefore, our $V_{\text{out}}$ measurements are a good representation of $V_{\text{max}}$ for objects that are well resolved, and of $V_{\text{max}}$ for objects that are marginally resolved.

The typical uncertainty on $V_{\text{out}}$, including the uncertainty on inclination ($\sim 5^\circ$) and position angles ($\sim 7^\circ$), is consistent with a half channel width. Fig. 3 shows the comparison between the corrected $W_{50}$ and the derived $V_{\text{out}}$ for our final bTFr sample of galaxies. For a fair comparison of the two different rotational velocity measures, we

$^3$Our MIGHTEE-H I galaxy sample has been shown to closely follow this relation during the data quality control check (Frank et al, in preparation).

$^4$i$H I > 20^\circ$ is somewhat more permissive than the classical approach where only galaxies with inclinations higher than 40$^\circ$ are included in the TFR samples (Read et al. 2016). However, we do not find any systematic effects associated with including galaxies of lower inclinations.

$^5$SNR and velocity resolution are the main reasons why 3D Barolo is not able to model the kinematics of some galaxies in our initial sample.

$^6$The machine-readable table, containing all measurements used in this analysis can be found at https://bit.ly/3zKpwdW.
correct our $W_{50}$ values by the kinematic inclinations produced during the second run of 3D Barolo. We also propagate the uncertainty of the kinematic inclination angles into the uncertainty on $W_{50}$. Overall the two measurements are in excellent agreement, with the mean of the difference ($W_{50} - 2V_{out}$) equal to 0.02 dex, and the standard deviation equal to 0.06 dex.

### 5 RESULTS

In this section, we present the statistical properties of the H I-based baryonic TFr beyond $z = 0$ for different rotational velocity measures ($W_{50}$ and $V_{out}$).

#### 5.1 Fitting method

Even though the bTFr is a basic linear relation, the choice of the fit is not trivial because errors on both axes as well as intrinsic scatter should be taken into account. There have been a number of studies, suggesting that the choice of the fitting technique can significantly affect the bTFr (Bradford, Geha & van den Bosch 2016; Sorce & Guo 2016). For example, it was shown that the slope of a TFr can be affected by Malmquist bias if a direct least-squares fit is used (Tully & Courtois 2012), which can be resolved with the use of an inverse fit (Willlick 1994). Moreover, it is important to keep in mind that the vertical scatter of the bTFr is highly slope dependent. Hence, an intrinsically tight linear relation may have a large vertical scatter due to the steep slope (Verheijen 2001; Ponomareva et al. 2017). It is important to take all these effects into account when studying the statistical properties of the bTFr. Lelli et al. (2019) compared three different types of linear fits and found that the maximum likelihood method that considered the orthogonal intrinsic scatter ($\sigma_\perp$) to be the preferred model. Ponomareva et al. (2017) and Stone, Courteau & Arora (2021) also found that the orthogonal linear regression model that minimizes the orthogonal distances from the data points to the fitted line better describes the intrinsic properties of any TFr.

For our study, we perform linear fits with a maximum likelihood model that takes the errors in both directions into account and assumes a Gaussian distribution to describe the intrinsic scatter along the perpendicular direction to the best-fitting line. We follow the prescriptions described in Lelli et al. (2019) and use the standard affine-invariant ensemble sampler for Markov chain Monte Carlo (MCMC) emcee (Foreman-Mackey et al. 2013) to map the posterior distributions of the main statistical properties: slope, zero-point, and intrinsic scatter. For the fit, we initialize the chains with 50 random walkers, run 1000 iterations and re-run the simulation with 1000 steps. The starting position of the walkers is set randomly within realistic ranges: slope [3.0, 5.0], zero-point [1.0, 5.0], and intrinsic orthogonal scatter ($\sigma_\perp$) [0.01, 0.25]. The convergence of the chains is checked visually.

Fig. 4 shows these posterior distributions for the bTFr based on both $W_{50}$, panel (a) and $V_{out}$, panel (b). Table 2 summarizes the values obtained for the slope, zero-point, $\sigma_\perp$, and standard observed vertical scatter ($\sigma$, see equation (3) in Ponomareva et al. 2017). Asymmetric errors are estimated at the 68 per cent confidence level of the marginalized 1D posterior distributions of the fitting parameters.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Comparison between corrected $W_{50}$ and rotational velocities measured from the rotation curves. The one-to-one relation is shown by the dashed line.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** The posterior distributions of the slope, zero-point, and intrinsic scatter for the bTFr based on $W_{50}$ (a) and $V_{out}$ (b). The red crosses and the solid lines show the maximum likelihood values. The black contours indicate 68 and 95 per cent confidence levels.
5.2 The evolution of the bTFr at $0 \leq z \leq 0.081$

Fig. 5 shows the bTFr for our sample galaxies for the two velocity measures: $W_{50}$, panel (a) and $V_{\text{out}}$, panel (b) colour-coded as a function of redshift. It clearly shows that the majority of galaxies lie along the best-fitting line, independent of the redshift.

However, a slight Malmquist bias can be seen in our sample. The low-redshift galaxies ($z \leq 0.04$) lie within the 2 dex mass range $8.6 \leq \log(M_{\text{bar}})[M_\odot] \leq 10.6$, while galaxies at $z > 0.04$ occupy a higher mass range from $9.7 \leq \log(M_{\text{bar}})[M_\odot] \leq 11.2$ (Fig. 6). To investigate if there is any evidence that the bTFr evolves over the last one billion years, we fit low- and high-redshift samples separately in the same manner as described in Section 5.1. The resulting fits are shown in Fig. 6 and Table 3 for both $W_{50}$ and $V_{\text{out}}$. We find the slopes and zero-points of both fits to be similar and consistent within the errors for $W_{50}$, as well as consistent with the best-fitting relation of the full sample. We therefore can conclude that our analysis does not suggest any evolution of the baryonic TFr during the last billion years.

Table 2. The statistical properties of the baryonic TFr based on two velocity measures, corrected $W_{50}$ and $V_{\text{out}}$, and obtained with the maximum likelihood orthogonal model.

<table>
<thead>
<tr>
<th>Sample size: 67</th>
<th>$W_{50}$</th>
<th>$V_{\text{out}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>$3.66^{+0.35}_{-0.29}$</td>
<td>$3.47^{+0.37}_{-0.30}$</td>
</tr>
<tr>
<td>Zero-point</td>
<td>$1.60^{+0.69}_{-0.82}$</td>
<td>$2.10^{+0.70}_{-0.86}$</td>
</tr>
<tr>
<td>Scatter ($\sigma$)</td>
<td>0.33</td>
<td>0.32</td>
</tr>
<tr>
<td>Intrinsic scatter ($\sigma_\perp$)</td>
<td>$0.07^{+0.01}_{-0.01}$</td>
<td>$0.07^{+0.01}_{-0.01}$</td>
</tr>
</tbody>
</table>

5.3 The bTFr at $0 \leq z \leq 0.081$ and different velocity definitions

Using the orthogonal maximum likelihood method, we find the slopes of the relations based on the two different velocity measures to be consistent within the uncertainties (Fig. 4, Table 2). However, it is somewhat surprising that $W_{50}$ yields a slightly steeper slope than $V_{\text{out}}$. Previous studies (Ponomareva et al. 2018; Lelli et al. 2019), which used different velocity definitions, find that the slope of the relation is the steepest when the flat part of the rotation curve ($V_{\text{flat}}$) is used as the velocity measure, and becomes shallower when other definitions such as $W_{50}$ or $V_{\text{max}}$ are considered. These trends are well understood, and attributed to the shapes of the rotation curves (Verheijen 2001; Noordermeer et al. 2007; Ponomareva et al. 2017). Maximum rotational velocities are measured in the inner parts of spiral galaxies and tend to overestimate the rotational velocity if compared to the outer regions where the rotation curves reach the flat part ($V_{\text{flat}}$). For dwarf galaxies, rotation curves do not reach the flat part, and the maximum rotational velocities tend to underestimate $V_{\text{flat}}$. Consequently, the slope of the relation will get shallower because the velocity of high-mass galaxies will be overestimated, shifting them to the right, while it will be underestimated for low-mass galaxies, moving them to the left.

Comparing our slopes and zero-points to the Lelli et al. (2019) relations based on $W_{50}$, $V_{\text{flat}}$, and $V_{\text{max}}$, we find that our measurements for $W_{50}$ are consistent within the errors, but our $V_{\text{out}}$ results are more consistent with their relation based on $V_{\text{max}}$ rather than $V_{\text{flat}}$. This suggests that $V_{\text{out}}$ in our study might be more representative of the maximum rotational velocity than of the rotational velocity measured at the flat part of the rotation curve. As mentioned previously, our $V_{\text{out}}$ measurements are a mixture of $V_{\text{max}}$ and $V_{\text{flat}}$, depending on the spatial

Figure 5. The bTFr with data points colour-coded as a function of redshift: panel (a) shows the bTFr based on the corrected $W_{50}$ as a rotational velocity measure; panel (b) shows the bTFr based on $V_{\text{out}}$. The best fit is shown by a solid black line, and the 1$\sigma$ uncertainty of the fit, sampled from the MCMC posteriors (Fig. 4) is shown with the shaded area.
In this paper, we present the first study of the HI-based bTFr over the last billion years using the Early Science data from the MIGHTEE survey. We are for the first time able to compare a higher redshift study to the local ($z = 0$) bTFr, derived from one homogeneous single survey, where observations and analyses of sources were treated in the same manner. This study aims to investigate the statistical properties of the bTFr based on two different velocity measures: corrected $W_50$ from the global HI line profile, and $V_{	ext{out}}$ measured from the resolved HI rotation curves. We derive resolved HI rotation curves at $z > 0$ for the first time using a fully automated kinematic resolution of a galaxy. Fig. 6(b) shows that the slope for the low-$z$ sample is steeper (although still consistent within the uncertainties), than for the high-$z$ sample. Interestingly, the slope of the low-$z$ sample is identical to the one found by Lelli et al. 2019 (3.85) with the relation based on $V_{\text{flat}}$, while the high-$z$ slope is more consistent with their slope for $V_{\text{max}}$. We therefore conclude that our $V_{\text{out}}$ is a good representation of $V_{\text{flat}}$ for the low-redshift galaxies, and mostly likely traces $V_{\text{max}}$ for the high-redshift galaxies that are naturally less resolved. This will be further tested when the new MIGHTEE survey data with higher velocity resolution becomes available.

Interestingly, we find no difference in the intrinsic scatter between the relations, based on different velocity measures as often found at $z = 0$ (Table 2). We find both relations to be relatively tight $\sigma = 0.07 \pm 0.01$, however, not consistent with zero intrinsic scatter within $3\sigma$ as suggested for $z = 0$ (Lelli et al. 2019). Future work with the full MIGHTEE-HI sample and higher velocity resolution will provide further constraints on the intrinsic scatter of the bTFr beyond $z = 0$.

6 SUMMARY AND CONCLUSIONS

In general, it is very encouraging that we find our results to be so consistent with the SPARC measurements. Not only because our HI data cover different redshift range, and are of different spatial and velocity resolution, but also because of the different methods followed to estimate the stellar masses of galaxies. While SPARC uses a nearly constant mass-to-light ratio at 3.6 $\mu$m, we use the SED-fitting technique (Section 3.1). It was shown by Ponomareva et al. (2018) that the chosen method to estimate the stellar mass of spiral galaxies can have a significant effect on the statistical properties of the bTFr, with the SED-fitting producing masses that yield the highest intrinsic scatter. However, our result suggests that it is not the SED-fitting per se, but the quality of the photometric data that affect the statistical measurements. The high quality of the photometry in the MIGHTEE fields allows us to recover a small intrinsic scatter independently of the method used to estimate stellar mass.
modelling software 3D Barolo. Our main results can be summarized as follows:

(i) The inclination of a galaxy is the main caveat for blind automated kinematic modelling, with 3D Barolo able to recover all galaxy parameters blindly, except for inclination. Therefore, inclinations should be measured carefully in advance either from the H I moment-0 maps or from the ancillary photometry, and provided as an initial estimate.

(ii) We find no evidence for evolution of the bTFr over the last billion years, independent of the rotational velocity definition used ($V_{50}$ or $V_{eq}$).

(iii) The bTFr over the last billion years is relatively tight with orthogonal intrinsic scatter $\sigma_{b} = 0.07 \pm 0.01$, comparable to the SPARC sample at $z \simeq 0$ ($0.035 \pm 0.006$ for $V_{50}$ and $0.04 \pm 0.006$ for $V_{max}$), but not consistent with zero intrinsic scatter within $3\sigma$. To be able to provide as accurate comparison as possible, we employ the same maximum likelihood fit as (Lelli et al. 2019), that considers the orthogonal intrinsic scatter.

(iv) We find the slopes of our relations to be consistent within the errors ($3.66^{+0.35}_{-0.29}$ for $V_{50}$ and $3.47^{+0.37}_{-0.36}$ for $V_{out}$) as well as consistent within the errors with the $z \simeq 0$ studies ($3.62 \pm 0.09$ for $V_{50}$ and $3.52 \pm 0.07$ for $V_{max}$). Unexpectedly, we find that the use of the corrected $V_{50}$ results in a steeper slope, suggesting that our definition of $V_{out}$ is consistent with $V_{max}$ for high-redshift galaxies and with $V_{int}$ for the low-redshift sample. We will test this further when the full data with higher velocity resolution will be available from the complete MIGHTEE survey. Nevertheless, our results showing consistency with the largest study conducted at $z \simeq 0$ are a major breakthrough in studying the H I-based bTFr and resolved H I kinematics at higher redshifts.

New observational facilities such as MeerKAT, have a potential to transform our knowledge about the H I distribution and kinematics at high redshifts, well before the SKA era. The MIGHTEE Large Survey Program is well underway, and will give us an opportunity to extend the current study up to $z \simeq 0.5$, including the redshift evolution directly in the relation. Improved velocity resolution will be essential for the detailed study of not only the statistical properties of the bTFr, but also of the mass models of galaxies beyond $z = 0$. MIGHTEE is strongly complementary with the LADUMA survey (Maddox, Jarvis & Oosterloo 2016), and combined they will provide crucial constraints on the evolution of H I up to $z \sim 1$, and to the current models of galaxy formation and evolution.

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http://www.astropy.org
DATA AVAILABILITY

The machine-readable table, containing all measurements used in this analysis can be found here. The complete fitting parameters produced for both bTFs can be found here.

The MIGHTEE-H I spectral cubes will be released as part of the first data release of the MIGHTEE survey, which will include cubelets (Shirley et al. 2021) and also soon from the Deep Extragalactic Visible Legacy Survey (Davies et al. 2021).

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

$b$TFRfit.zip
master_sample_bTFr.txt

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