Investigating HI size-mass relation in TNG50 and MIGHTEE-HI

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Resumen. Cosmological simulations can be thought of as synthetic galaxies in a box. The simulations are generally computationally expensive hence many physical processes need to be implemented through sub-grid prescriptions leading to some discrepancies between observational and simulated data. In this study, our goal is to investigate to which extent TNG50 galaxies follow the MIGHTEE-HI observations. We use the HI size-mass relation to study the consistency of the TNG50 galaxies in comparison to the MIGHTEE-HI galaxies. The TNG50 sample follows the same logarithmic relation derived from previous work, between the diameter (D_{HI}) and the mass (M_{HI}) of HI discs. We measure a slope of $0{,}478 \pm 0{,}004$, an intercept of $-3{,}172 \pm 0{,}030$ and a scatter of 0,29 dex. In future work, we intend on investigating the large scatter in our results as well as predict the cosmic evolution of the HI size-mass relation.

1. Introduction

Atomic hydrogen (HI) provides the primordial gas that serves as the raw material for the build-up of stellar mass. Observations of HI in galaxies provide a powerful probe to study galaxy formation and evolution mechanisms. Improvements in the sensitivity of observational surveys have made it possible to detect fainter HI structures than previous surveys could. Consequently, allowing for a better census of the total HI content in galaxies but also elucidates the interactions they have with their environment and their importance in galactic evolution.

Global HI relations, such as the HI mass vs stellar mass, neutral hydrogen mass function (HIMF), neutral hydrogen velocity function (HIVF) and the Tully-Fisher relation place constraints on cosmological models of galaxy formation and evolution. HI scaling relations in nearby disc galaxies, especially the tight HI size-mass relation, also provide important constraints. In this study, we will reproduce this relation for the TNG50 HI discs and test their consistency towards the MIGHTEE-HI observed galaxies.

The HI size-mass relation was first investigated by Broeils and Rhee in 1997 (2) and parametrised as follows:

$$log(R_{HI}) = \alpha \times log(M_{HI}) - \beta \tag{1}$$

where α and β represent the slope and the intercept, respectively. R_{HI} is in units of kpc and M_{HI} is in units of $M_{\odot}$. A slope of $0{,}510 \pm 0{,}04$ and an intercept of$-3{,}27 \pm 0{,}06$ was reported. Suggesting that the average HI surface density in these galaxies is nearly constant.

Furthermore, Wang et al 2016 (6) reproduced the relation using the largest observational work-to-date. A galaxy collection of over 500 galaxies from different surveys, ranging over five decades in M_{HI} were studied. Accordingly reporting a slope of $0{,}506 \pm 0{,}003$ and an intercept of $-3{,}25 \pm 0{,}009$. These results produced a noteworthy tight scatter relation of 0.06 dex. Moreover, other studies of observational and galaxies have also reproduced the HI size-mass relation (e.g. Marinacci et al 2017(7), Bahé et al 2016 (8)). The general consensus is that the relation implies that HI galaxy discs of different types of galaxies are very self-similar. Suggesting that all galaxies experience a similar evolutionary process so long as they remain gas-rich. This contradicts what was reported by Lelli et al 2016 (9) which equally noted that low-mass galaxies have denser HI discs in comparison to their more massive counterparts. A natural consequence due to the smaller galaxies having lower angular momentum.

A more recent study by Rajohnson et al 2022 (3) presented the homogeneous MIGHTEE (MeerKAT International GHz Tiered Extragalactic Exploration) -HI EARLY Science data. This sample consisted of 276 galaxies, ranging 4 orders of magnitude in HI mass at redshift zero. The study reported a slope of$0{,}501 \pm 0{,}008$, an intercept $-3{,}252^{+0{,}073}_{-0{,}074}$ and corresponding observed scatter of 0.057 dex.These results are in good agreement with what is currently reported in the literature. This makes the HI size-mass relation a good candidate to place a strong constraint on the way that different processes, including gas inflow, star formation and feedback balance in numerical models of galaxy formation and evolution.

In this work, we present the HI size-mass relation for galaxies from the TNG50 cosmological simulation. We will be using simulated data produced by Gebek et al in preparation to study the correlation between TNG50 galaxies and that of MIGHTEE-HI. Our goal is to investigate the consistency between TNG50 galaxies and observations (i.e. MIGHTEE-HI).

1.1. TNG50

IllustriusTNG (5) is a suite of cosmological magnetohydrodynamical simulations of different volumes and resolutions, which constitutes of TNG100, TNG300 and TNG50. TNG50 is the terminarch of the three projects, consisting of over 20 billion resolution elements and capturing spatial scales of $\sim$ 100 parsecs. The 50 Mpc box is sampled by 2160^3 dark matter particles, with masses of $4 \times 10^5 M_{\odot}$ and 2160^3 initial gas cells, with masses of $8 \times 10^4 M_{\odot}$.Furthermore, TNG50 incorporates the comprehensive TNG model for galaxy formation and evolution physics. Subsequently occupying a unique combination of large volume and high resolution. The large volumes feature allow for statistically robust comparison of entire galaxy populations whereas the high resolution simulations more reliably model the cold, star-forming gas. TNG50 has proven to be an instrumental theoretical tool for comparison through the production of mock observations of simulated data. Such studies have be recorded in Diemer et al 2019 (10) as well as Stevens et al 2019 (11) just to name a few. In this project we will exploit the statistical and resolution capabilities of TNG50 and compare them against the MIGHTEE-HI Early Survey data.

1.2. MIGHTEE-HI

Additionally, important to this work is the MIGHTEE-HI observational survey. MIGHTEE consists of 8 Large Survey projects of MeerKAT (13) . The HI survey, MIGHTEE-HI, focuses on HI emission, absorption and polarisation in galaxies. MIGHTEE-HI is one of the first deep, blind, medium-wide interferometric surveys for HI. We have used the Early Science data (Maddox et al 2021) and have followed Rajohnson et al 2022 to reproduce the observed MIGHTEE-HI size-mass relation. A 4k spectral line correlator mode was used to collected the data. The correlator had a channel width of 209 kHz and a velocity resolution of 44.1 $km.s^{-1}$ at redshift zero. Two of the four MIGHTEE fields were used to carry out these observations. Namely; XMMLSS -covering approximately 3.5 deg^2 of the sky - and COSMOS which covers 1.5 deg^2 of the sky.

2. Methodology

Gebek et al in preparation undertook a systematic study of models that predicts the HI and H_2 fraction and applied them to the TNG50 simulation galaxies. The modelling of the HI-to-H_2 transition and the relevant details of the TNG50 simulations are discussed at length in Gebek et al in preparation. The HI-to-H_2 model by Gnedin & Draine 2014(4) has been implemented as the partitioning scheme of choice to produce the moment0 maps used in this study. The Gnedin & Draine 2014 (4) model relies on surface densities rather than volume densities. The moment0 maps were produced by applying the HI-to-H_2 model. The UV field plays an important part in the destruction of hydrogen which is required for the HI-to-H_2 transition partitioning process. The radiative transfer code SKIRT has been employed to estimate the UV radiation field. The UV field is calculated by propagating light from star-forming regions and evolved stars through the dusty interstellar medium, taking dust attenuation into account.

2.1. Galaxy selection

TNG50 can fully represent simulated galaxy populations spanning $10^7 < \frac{M_\odot}{M_*} < 10^{11,5}$. However, in our study we worked with a base sample of $M_* > 10^7 M_\odot$ and $M_g > 10^6 M_\odot$ is imposed on the galaxies. Correspondingly, these criteria produced feasible result when estimating the UV radiation field in SKIRT.

The diameter of the HI galaxy disc is conventionally defined as $\Sigma_{HI} \sim 1 M_\odot pc^{-2}$. Furthermore, an advantage of measuring R_{HI} at $1 M_\odot pc^2$ is that it is more easily measurable for small HI discs that are close to being unresolved. Some of the galaxies in this sample have surface densities lower than $1 M_\odot pc^{-2}$, these are thus negated. A stellar-mass-selected and HI-rich-selected samples of 12 611 and 10 652, is obtained respectively. For the purpose of this study we will only focus on the HI-rich-selected sample, which is a sample retention of 83.35 % from the stellar-mass-selected sample. We do not cut the galaxy sample any further at this point.

2.2. Determine the diameter of the TNG50 galaxies

In this section we apply the 2D Gaussian fit presented in equation (2), to determine the HI diameter of the galaxy

$$f(x, y) = Aexp(-(a(x - x_0))^2 + 2b(x - x_0)(y - y_0) + c(y - y_0)^2 \tag{2}$$

where A is the amplitude of the Gaussian peak in $M_\odot pc^{-2}$, (x_0, y_0) represents the central position in pixels. The parameters a, b and c are defined as:

$$a = \frac{cos^2(\theta)}{2\sigma_X^2} + \frac{sin^2(\theta)}{2\sigma_Y^2} \tag{3}$$

$$b = \frac{sin2(\theta)}{4\sigma_X^2} + \frac{sin2(\theta)}{4\sigma_Y^2} \tag{4}$$

$$c = \frac{sin^2(\theta)}{2\sigma_X^2} + \frac{cos^2(\theta)}{2\sigma_Y^2} \tag{5}$$

The position angle is represented as θ in radians, σ_X and σ_Y are the semi-major and semi-minor axis of the disk, respectively.

This study applies a framework which automatically calculates the diameter and mass of the individual HI disc galaxies. We select galaxies which have surface densities larger than $1M_{\odot}.pc^{-2}$. The sample then undergoes the 2D Gaussian fitting process. Similarly, the initial conditions for the amplitude, a,b, c and θ parameters are calculated for all the individual galaxies. A python package called differential evolution is used for this role. This package looks for the optimal initial conditions by searching for the global minima within a given parameter space. These are then assigned as the initial conditions. This helps decrease the run time of the code as well as saves the memory due to the sheer quantity of the galaxy sample.

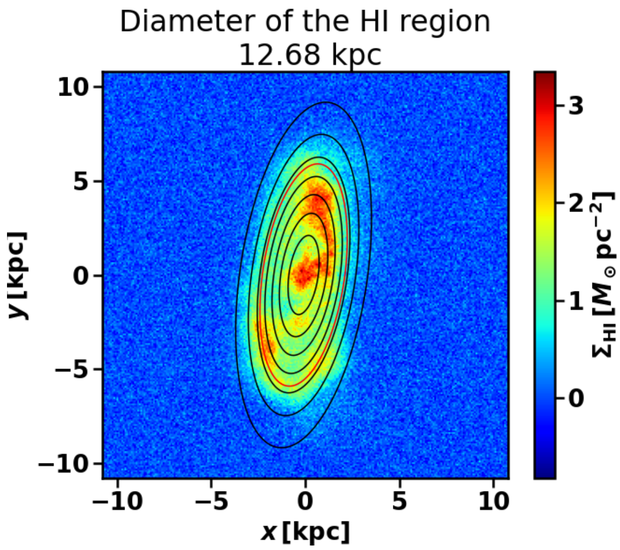

Figura 1. This HI moment0 map shows an example of a galaxy in our TNG50 sample. The red contour demarcates the region at which $\Sigma_{HI} \sim 1M_{\odot}pc^{-2}$. The size and mass of this galaxy are $D_{HI} \sim 12{,}68$ kpc and $M_{HI} \sim 3 \times 10^8 M_{\odot}$ respectively.

3. Results and discussion

In this section we will be discussing the results obtained from this study. Figure (1) and Figure (2) show the HI moment0 map of a HI-rich galaxy from our sample set and the TNG50 HI size-mass relation at $z \sim 0$, respectively. The red contour line seen in Figure (1) demarcates the region at which $\Sigma_{HI} \sim 1M_{\odot}.pc^{-2}$, which defines the R_{HI} of the galaxy disc The blue points represent the galaxy population and the green shaded area represents the 3σ region of this sample. Additionally, the two straight lines represented in black and red denote the MIGHTEE-HI (3) and TNG50 HI size-mass relation, respectively. These lines are represented by the the best-fit seen in equation (1). Our sample selection includes galaxies of different orientation and morphology. Nonetheless, a line of best fit through our data parametrises the TNG50 HI size-mass relation as follows

$$log(D_{HI}) = 0{,}48 \pm 0{,}004 \times log(M_{HI}) - 3{,}17 \pm 0{,}030 \tag{6}$$

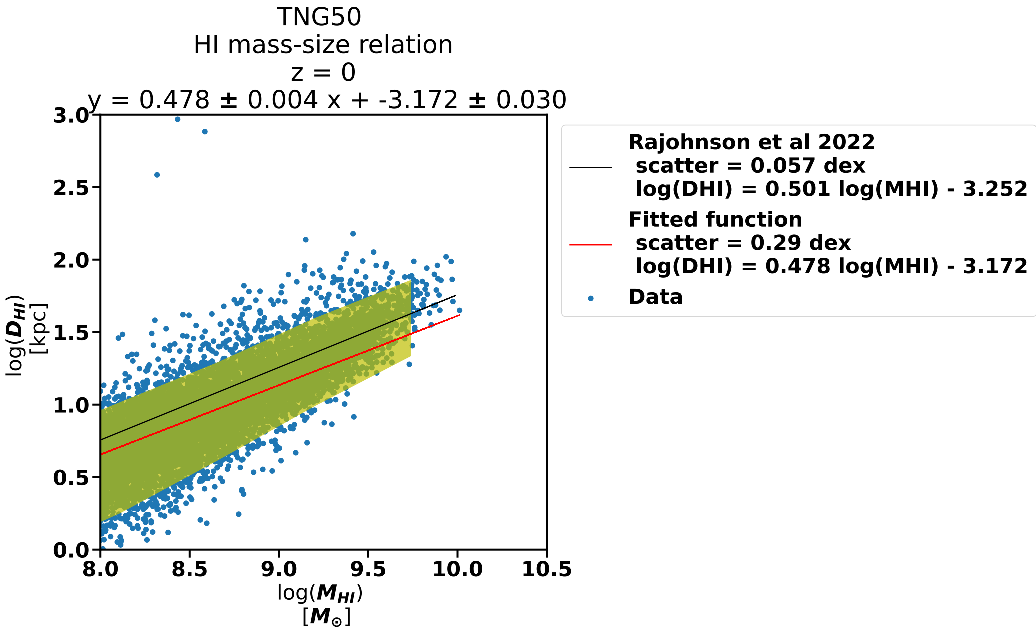

Figura 2. This plot shows the TNG50 size-mass relation. In the y-axis we have the size of the galaxy in kpc and in the x-axis we represent the HI size in $M_{\odot}$.

Observationally the relation is extremely tight, with only 0.06 dex (6) and 0.057 dex scatter (3). Likewise, our simulated galaxies reproduce the same general trend seen in observations. This trend depicts that larger HI size discs corresponds to a higher HI mass which is in agreement with other studies.

Rajohnson et al 2022 (3) reported a sample galaxy population of M_{HI} ranging from $M_{HI} \sim 10^8 - 10^{11,5} M_{\odot}$ with corresponding diameter ranges between $D_{HI} \sim 1 - 2{,}3$ kpc. In this study a similar mass range, $\sim 10^8 - 10^{10} M_{\odot}$, was investigated. Resulting to HI disc galaxies diameters between $0{,}1 - 2$ kpc which are slightly lower than what was reported in Rajohnson et al 2022 (3).

Nevertheless, the TNG50 HI size-mass relation is not in too much tension with what has been reported in other studies. Although our results show more scatter the best-fitting parameters are consistent with the observational findings of the literature such as (3) and (6). This implies that the average HI surface densities within TNG50 galaxies is an approximate constant and thus the mechanisms which balance the HI distribution in all the galaxies. Further investigation of the feedback mechanisms could improve on these results.

4. Conclusions

We have presented the HI size-mass relation of the TNG50 HI galaxy discs. The sample contained $\sim$ 10000 HI-rich galaxies at redshift zero. The predictability of the HI size-mass relation makes it a good candidate for testing the accuracy or consistency of any model or simulation of galaxy evolution.

We measured galaxy HI masses and used the 2D Gaussian fitting method to estimate the size of the HI galaxy discs. The main results of our study are as follows :

- In our analysis we have reported a R_{HI} within the $1-10kpc$ range with corresponding M_{HI} ranges from $\sim 8{,}5 \times 10^7$ to $\sim 1{,}3 \times 10^9 M_\odot$.
- We obtained a line-of-best fit of $log(D_{HI}) = 0{,}478 \pm 0{,}004 \times log(M_{HI}) - 3{,}172 \pm 0{,}030$ for the TNG50 HI disc galaxies. There is tension between our results and Rajohnson (3) (as seen in Figure (2)). This maybe due to an underestimate of the total neutral gas abundance at z = 0 by about a factor of two.
- Galaxies in hydrodynamical simulations and semi-analytical models have an analitically derived limit on its scatter of $\leq$ 0.1 dex. In this study a scatter of 0.29 dex was obtained. Our next task is to understand the reason behind this large scatter and improve this relation.

In this work we have successfully show that the HI size mass relation can be used as a tool to investigate the agree-ability of simulated galaxies.

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