The growth of stellar discs in MW-like galaxies in TNG50

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Abstract: The objective of this project has been to study the implications that a merger event has in the evolution of a galaxy, and whereas it can justify the formation of a thick disk akin to the one we observe in the Milky Way. In order to analyse this phenomena, we have looked at the metallicites, densities and velocity dispersion of the stellar population of a galactic disk for two galaxies; one which experienced a merger during its evolution and one that developed without. We also compared our results to those found in the literature in order to evaluate their validity, all while using available data from TNG50-1 simulation database.

I. Introduction

Studying and understanding the cosmos is essential for a correct comprehension of the laws of physics that govern our universe. The physical processes that occur in the context of cosmology are not bound by the same limitations as those on Earth; as such, many physical phenomena that would be impossible to replicate in a laboratory are only able to be understood through the lenses of astrophysics and cosmology.

However, the real physical universe is a system of incredible complexity, encompassing a myriad of structures ranging from planetary systems to galaxies. As a consequence of this, the study of the different cosmological phenomena is often done through the use of simulations. This is the procedure that this project will follow too. The simulation database that we will employ will be that of the Illustris TNG Project, specifically, the TNG50-1 simulation.

The TNG50-1 simulation database consists of a set of magneto-hydrodynamical simulations (Annalisa Pillepich et al.) which allows us to study the characteristics, formation and evolution of galaxies and the astronomical bodies within it. This particular database consists of a 51.7 Mpc box with data from 100 snapshots up to redshift 14.98, which corresponds to a maximum lookback time of 14Gy.

In this project, we will focus on the phenomenon of a merger for Milky Way-like galaxies and how it affects the vertical velocity dispersion and vertical and surface density of the stars within compared to a galaxy that evolves without a significant merger. We will also look at the iron and α contents of our galaxies to see if a merger affects its metallicity contents.

We also aim to compare our results with those gathered by authors such as Amina Helmi et al. and verify if they agree with their hypothesis. Amina Helmi's paper, predicts that the thick disk of the Milky Way was formed partly due to a merger event with a large dwarf galaxy (the Gaia-Enceladus) through the use of idealised simulations that assume a thin disk structure at the early stages of the galaxy. However, it does not consider the effects of the cosmological growth of galaxies. We will study this growth through the use of TNG50 simulation database.

For our study, we have sampled the TNG50-1 database and selected galaxies that are analogues to the Milky Way. Through a careful inspection of their stellar, gas and dark matter evolution plots across time, we selected two galaxies; one with a merger and another one without a *significant* merger event.

Since our interest is to study these Milky Way analogues to better understand the Milky Way itself, it is reasonable to compare our results with those found in the literature. We will compare the behaviour of our stars to those found by authors Joss Bland-Hawthorn, Ortwin Gerhard for our surface density profiles and authors Lawrence M. Widrow et al for the vertical density in order to verify the accuracy of our simulation data.

As a final clarification, we must note that we will be using the words *subhalos* and *galaxies* often interchangeably during this project. This is generally not correct as not all subhalos can be categorised as galaxies. However, since our first step for this study is to sample such subhalos so that we only keep those that correspond to MW-like galaxies, this denomination then becomes accurate.

II. Experimental procedure

A. Sampling of MW-like galaxies

In this project we are only interested in galaxies that present Milky Way - like morphologies. As such, it is essential to sample the given simulation data so that the studied galaxies meet such criteria. TNG50-1 has a total set of 5688113 subhalos at redshift zero. For the scope and purpose of this project, our sampling will be done over a set 100000 subhalos ordered by their mass. Our procedure will follow similar steps as Annalisa Pillepich et al.

The first step will consist on filtering our subhalos by their mass properties and the cosmological environment where they reside.

1. We will restrict the stellar mass of the subhalo in the range of $10^{10.5}M_\odot$ - $10^{11.2}M_\odot$.
2. The galaxy must be isolated from other massive galaxies *(with a stellar mass greater than* $10^{10.5}M_\odot$*)* within a 500 kpc radius.

Based on these criteria, our sample of 100000 subhalos was reduced to 122 galaxies. Now we can go onto the next part of the process. This part will consist on visual inspection of the galaxy stellar density profile.

For a galaxy to be accepted for our analysis, its XY stellar density profile must be disky, while its XZ profile must appear flat in the frame of reference where the direction of the total angular momentum of the galaxy constitutes the z-axis. This rotation process will be explained in more detail in further sections. If we apply a these criteria to the XY and XZ stellar density profiles we obtain a final set of 97 galaxies.

B. In situ and ex situ stars separation

Now that we have our galaxies, since we are studying merger events, it is interesting to know if a star belongs to the main galaxy (in situ) or if it has arrived externally (ex situ). Unfortunately, TNG50-1 does not have any catalogue with these data available to the public. Our first approach was to separate in situ from ex situ with a kinematic analysis following the steps suggested by Cecilia Scannapieco's paper, where we considered the ex situ stars those belonging to the dispersion dominated halo defined by the circularity ε peaks. However, this method turned out to be insufficient to obtain achieve an accurate in situ and ex situ division. Then, we attempted to use a method where we tracked the stars IDs of the subhalos back through redshifts, and label as in situ those that were formed in the main progenitor of our galaxy. However, since we were working on our simulations through the API, such an extensive query was too time demanding, so it was instead made through the virgo node where the Illustris TNG50-1 is locally stored at the Max Planck Institute for Astrophysics in Garching.

C. Rotation procedure

The TNG50-1 data is provided in the frame of reference of the *'lab'*, meaning that a galaxy will rarely be aligned so that the disk is in the x-y plane and the angular momentum in the z-direction. This makes it complicated to calculate properties such as vertical velocity dispersion and surface and vertical densities. Fortunately, the process to rotate a galaxy so that it aligns with our desired axis is not too complicated. The process is as follows:

1. First, we calculate the angular of all the stars within a 5 kpc radius from the center of the galaxy. The angular momentum being:

$$\vec{J} = \sum_{r_i \leq 5\ \text{kpc}} (m_i \vec{r_i} \times \vec{v_i}) \tag{1}$$

2. Then, we rotate our galaxy using Rodrigues' formula so that the rotation axis is perpendicular to both the overall angular momentum and the z-direction, so that it obeys $\vec{u}_{rot} = \vec{J} \times \hat{z}$.
3. To refine our rotation, we then take a cylinder of initial height and radius equal to 5 kpc and repeat the rotation process. We then iterate by reducing the height of the cylinder each step until the difference between the rotation angle of two subsequent iterations is small enough.

D. Velocity dispersion and vertical and surface density equations

We will calculate the vertical density through vertical bins and the surface density through rings in the XY plane. The equations we will follow in order to evaluate them are quite straight forward. For the densities:

$$\rho_z = \frac{\sum_i m_i}{\Delta z} \tag{2}$$

$$\sum{}_R = \frac{\sum_i m_i}{\pi((R+\Delta)^2 - R^2)} \tag{3}$$

where Δz and Δ are the width of each vertical bin and the separation between two consecutive rings respectively. We have chosen a value of 2 kpc for each. Lastly, for the vertical velocity dispersion, we will measure it through the statistical deviation with respect to the mean value, so that:

$$< v_z^n >= \frac{1}{N} \sum_i v_{z,i}^n \tag{4}$$

$$\sigma_z = \sqrt{< v_z^2 > - < v_z >^2} \tag{5}$$

where N is all the stellar simulation particles we are averaging. In order to study the galactic disk, we will only focus on the regions corresponding to 5 kpc $\leq$ r $\leq$ 20 kpc and $|z| \leq$ 5 kpc.

III. Study of a merger event

A. Metallicities of a merger event

It is known that some galaxies present a double sequence shape in their [α/Fe]-[Fe/H] diagram, with a high [α/Fe] region associated to the thick disk and the lower region associated with the thin disk. The Milky Way presents this bimodality. We have selected two galaxies; one possessing such structure, and another one that does not. Joss Bland-Hawthorn's paper greatly delves into this phenomenon. Due to the limitations of this project, we will not dive into that much detail, since we will focus our attention on the density and velocity dispersion profiles.

Fig 1. shows the stellar abundances of iron ([Fe]), hidrogen ([H]) and α processes related elements, the most relevant being oxygen, neon, magnesium, silicium and sulfur ([α]) compared to the abundances of the sun. We

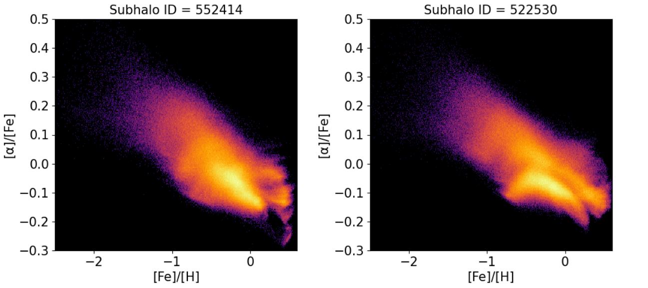

FIG. 1: [α/Fe]-[Fe/H] abundances diagram for the stars of two different galaxies. The colours scale with star density; with brighter colours indicating a higher concentration of stars.

can see subhalo 522530 possesses a double sequence region where the diagram *bounces back* in the -1 $\leq$ [Fe/H] $\leq$ 0 region. A more detailed study which followed the steps of Joss Bland-Hawthorn's paper would consist on separating the diagram into different height bins. Since this is not the main focus of our project, we will limit ourselves to identifying whether this effect shows indications of being caused by a merger event, to achieve this, we will first look at the stellar mass evolution of both galaxies of study.

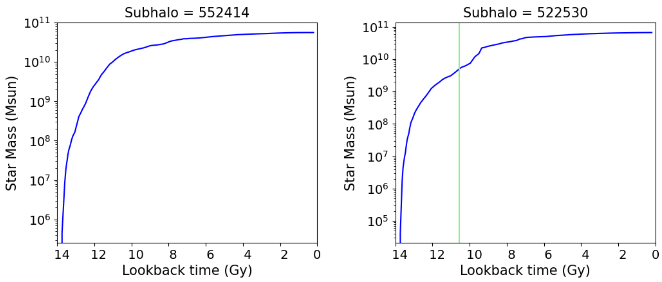

FIG. 2: Stellar mass evolution (in solar masses) as a function of lookback time (in Gy), which indicates the age from the present at redshift zero. The vertical axis is logarithmic.

Looking at fig 2. we can see that, while the subhalo 552414 follows a steady growth as it ages, there is a clear change in behaviour around 10 Gy of lookback time (at redshift 1.53) for the subhalo 522530, which indicates the presence of a merger.

To check its correlation for the double sequence we can see in fig 1., we can look at the gas surface density, since it is the gas that will bring in the metallicity, which will then be consumed to give rise to stellar birth. To check this, we have inspected the gas density profile at a redshift immediately before the merger event and at another immediately after. We will also plot the same profile but by filtering the gas to the metallicity correspondent to the double sequence region.

If we now look at fig 3., we can clearly see that before the merger, the gas did not possess enough particles within the filtered [α/Fe]-[Fe/H] window to justify the presence of a double sequence. However, after the merger, the amount of gas with metallicity akin to the double sequence region is shown to have increased greatly. We may compare the ratio of gas particles within the metal filtered region with respect to the total number of particles. Before the merger, that ratio is only of 2.52%, while after the merger it has grown to 27.62%, showing a significant increase. Therefore, it is reasonable

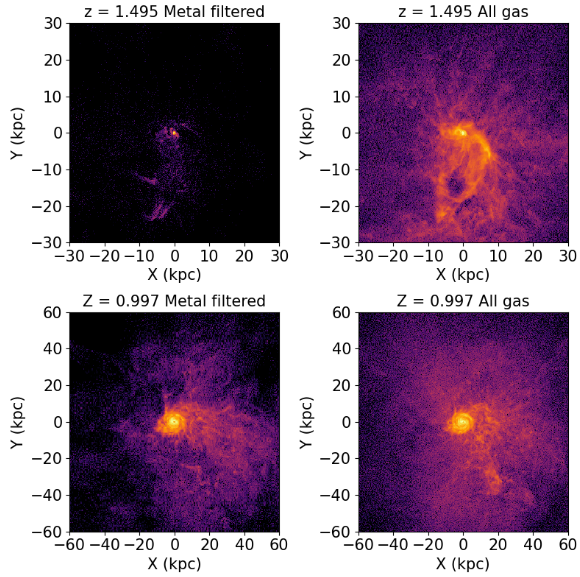

FIG. 3: Gas surface density for the nearest redshift snapshot before and after the merger event at redshift 1.53 for the subhalo 552530. The colours estimate the number density of particles per colour bin, with brighter colours indicating largest gas concentration. On the left, only gas corresponding to the double sequence metallicity is shown. On the right, we show all the gas particles.

to conclude that the double sequence was triggered by a merger event for our sample galaxy.

B. Stellar densities and velocity dispersion of the galactic disk

Now we shall analyse the results found for both the disk densities and the velocity dispersion of the stars that form it. We note that all of the following plots have been done taking into account only in situ stars. First, we will study the density profile of our galaxies. Our procedure will follow the indications of Joss Bland-Hawthorn, Ortwin Gerhard and Lawrence M. Widrow's papers, who establish that both the vertical density and surface density of a galaxy will follow sech^2 shape. However, we will take the approach of Joss Bland-Hawthorn, Ortwin Gerhard's paper by considering the results proportional to an exponential law, so that the final densities follow the equations:

$$\rho_z \propto exp(-|z/z_o|) \quad \text{and} \quad \sum_R \propto exp(-R/R_C) \qquad (6)$$

1. Density profiles

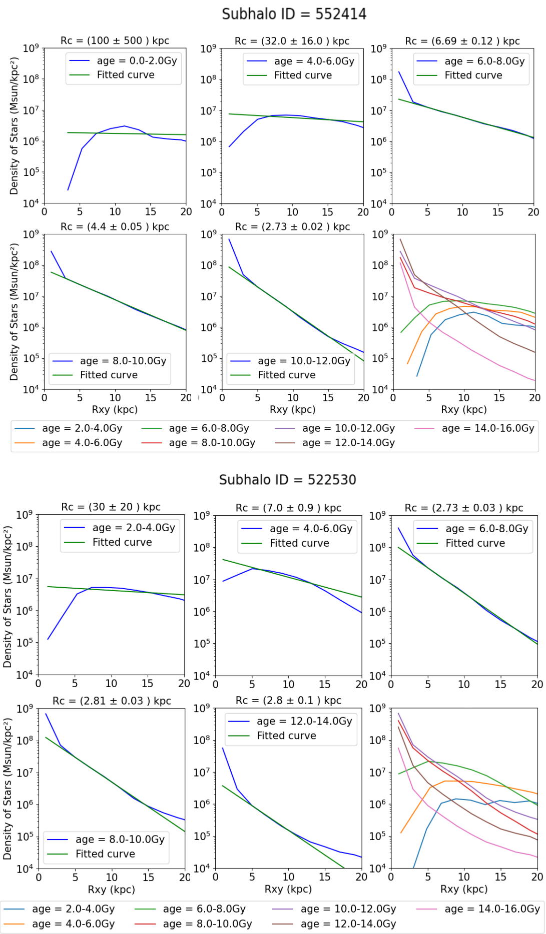

FIG. 4: Plots for the surface density of the stars within the galaxy disk for our two galaxies separated by age bins as a function of the distance from the centre of the galaxy parallel to the surface. The vertical axis is logarithmic. The scale length R_C is shown for some selected significant age bins. A figure with all of the age bin surface densities is also shown.

Looking at fig 4. our surface density results mostly agree with the literature (Jo Bovy and Hans-Walter Rix). For the older star populations the behaviour of the stars in the disk is close to the predicted exponential fit, with values in the range of $2 \leq R_C \leq 5$ kpc. However, this tendency is lost at ages ≤ 6 Gy. This is an anomalous behaviour that does not occur in the Milky Way. Nevertheless, we must remember that these galaxies are just analogues, and may be subject to different conditions than the Milky Way, which may cause atypical behaviours such as this.

In Jo Bovy's paper it is stated that the thick disk tends to have a shorter scale length. We can see that, for the older age bins the subhalo with a merger (subhalo 552530) does have shorter scale lengths than the galaxy without a merger event for all well-behaved age bins, which would point to the presence of a more dispersion dominated thick disk.

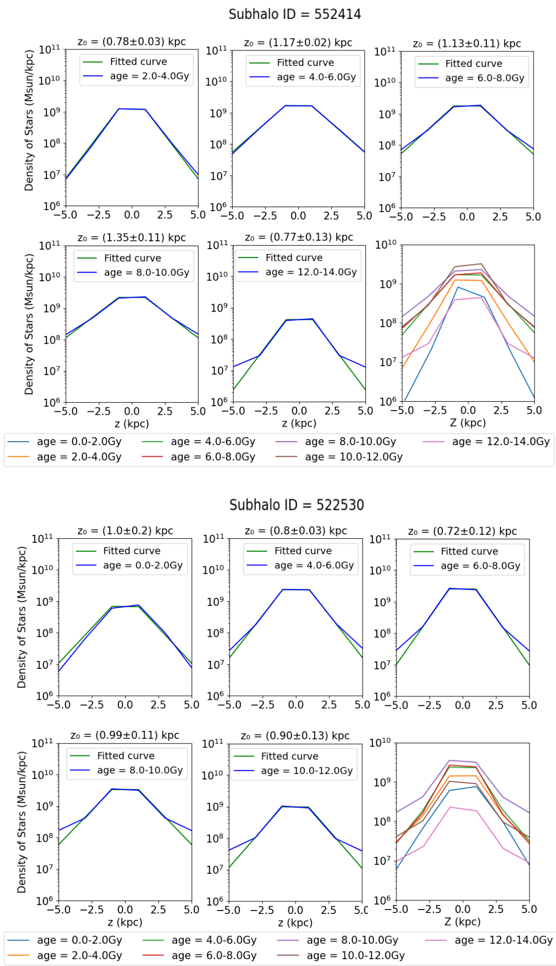

FIG. 5: Plots for the vertical density of the stars within the galaxy disk for our two separated by age bins as a function of the vertical distance from the centre of the galaxy. The vertical axis is logarithmic. The scale height z_0 is shown for some selected significant age bins. We also show the figure with all the age bins together.

Moving on to the vertical density shown in fig 5., Lawrence M. Widrow's paper explains a model in which the vertical density of the stars within the galactic disk can be related to a wavelike perturbation that can contribute to the heating phenomena within said structure. Lawrence M. Widrow's proposed model assumes an equilibrium model with a scale height $z_0 = 1$ kpc. If we look at our results, we can see that all of our scale heights are close to that proposed value, within the range of 0.72 kpc $\leq z_0 \leq 1.35$ kpc. Of course, our results vary depending on the stellar age, and while this was not focused upon in the aforementioned paper, it is mentioned in Xiangcheng Ma's paper, where it states that older stars ought to have a larger scale height. We verify this behaviour for our stars at the non-merger subhalo (552414) for ages ≤ 10 Gy, while the behaviour is more erratic for the subhalo with a merger (552530).

2. *Vertical velocity dispersion profiles*

Lastly, looking at fig 6., we may compare the shape of our vertical velocity dispersion with the ones present in the literature (Jason L. Sanders, Payel Das). While they separated the velocity dispersion in radial bins; we studied the overall structure of the disk. As such, our results are closer to those of author Robert J.J. However, for both cases we see that older stellar ages possess higher velocity dispersion, which is in accordance with our results. We can see that, at the moment of their birth at higher redshifts, older stars had a larger velocity dispersion than the youngest stars we see at the present at lower redshifts. This indicates that older stars were born in an already turbulent disk in the past, rather than a cool thin disk.

We also observe that the galaxy with a merger experiences a jump in dispersion velocity at the moment of the merger, which appears to indicate that such event would have played a role in the heating of the disk compared to the galaxy without a merger, which has a more homogeneous family of lines for the different redshifts. However, we also see that at approximately redshift 0.7 both galaxies start to cool down, which would suggest the presence of trapping effects or material being formed in the midplane of the disk.

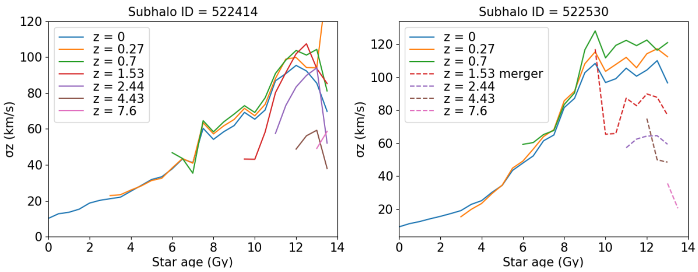

FIG. 6: Plots of the vertical velocity dispersion (km/s) as a function of the stellar age (Gy) of the galactic disk for our two galaxies. The age is with respect to the current day age at redshift zero.

IV. Conclusions

In our first part of the project, our study of the gas metallicity confirmed that the presence of a double sequence in the [α/Fe]-[Fe/H] was caused due to the merger event for our sample galaxies. We then looked at the disk stellar density profiles. Our surface density plots confirmed that the galaxy with a merger possessed lower scale lengths than the case without a merger for all well-behaved age bins. We then looked at the vertical density, and verified that our results were consistent with a Robert J.J's equilibrium model. Lastly, we studied the vertical velocity dispersion of the stellar disk. We found that there was a clear jump in the dispersion magnitude between the merger event and redshifts post-merger, while the non-merger galaxy had a more bundled family of dispersion lines, which pointed to the merger having an partial influence in the heating of the disk. However, the difference in dispersion magnitude for the two subhalos was not substantial enough to point to the merger as the main agent of the heating that would develop the thick disk. We also found that older stars were born with larger dispersion velocities compared to young stars at the present, which suggests that they were born in a turbulent disk rather than a cool thin disk as Amina Helmi's paper suggested. We also found that the disk does not heat indefinitely but there is a point around redshift 0.7 which triggers a cooling phase. This effect would need a more in depth study of its own, we can merely theorise that it may be due to trapping effects or material being formed in the disk midplane, as the disk grows in mass thus increasing the restoring force about the midplane.

V. Acknowledgments

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