Retrospective study of galaxy formation in IllustrisTNG and their HI asymmetries

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Abstract

This is a large scale study of 1052 dark matter sub-halos in the TNG100-1 simulation from IllustrisTNG at redshift $z = 0$ and within the $10^{11} - 10^{13.5} M_\odot$ range. Using an asymmetry calculator and Illustris catalog data, I studied the relationship between integrated HI flux asymmetries and sub-halo mass, group halo mass, metallicity, and primordial accretion rate. There is no apparent relationship with metallicity, but there was an observed relationship between asymmetry and sub-halo mass, halo mass, and accretion rate. I also observed the progression of asymmetry over the course of the entire lifespan of four halos.

Introduction

Radio astronomy utilizes emission lines from different elements and compounds to map out and study galactic structures. A crucial element to study is neutral hydrogen (HI) because it is the most common and very representative of baryonic mass distribution in galaxies. However, it is more common to observe the integrated HI spectrum, and not spatially resolved gas. When we observe these emissions, we see that they are spread across a range of frequencies due to rotation of the galaxy. From our perspective, as the galaxy rotates, some of the HI is blue shifted and some of it is red shifted. If the mass and motions are perfectly axisymmetric, then we would see an equal amount of HI blue and red shifted; otherwise the galaxy is asymmetrical.

Asymmetries in HI distributions in galaxies have been studied for some time now; however, the direct cause for a large proportion of asymmetrical galaxies remains unknown (Richter et al. 1994; Haynes et al. 1998). In nature, we observe that a monumental amount of galaxies that have likely not undergone a recent merger may be significantly asymmetric, over 50% (Richter et al. 1994). Galaxies which have undergone recent mergers are expected to be asymmetrical, so studies are done with a sample of galaxies which do not show signs of a recent merger (Bournaud et al. 2005). Ongoing theories suggest that the asymmetries may be due to gas accretion from dark matter halo mass, the total mass of the overdensity of dark matter in which a galaxy resides. Essentially, cold gas inflow, which is more frequent at lower dark matter halo mass (Bournaud et al. 2005; Keres et al. 2005), is causing the galaxy to be asymmetrical.

Studying galaxy formation is a difficult task because galaxies morph over very long periods of time, and many properties, such as dark matter halo mass, are difficult to estimate. To combat this challenge and better understand galactic phenomena, such as HI asymmetries, we use computer simulations. IllustrisTNG is a series of large, cosmological magnetohydrodynamical simulations of galaxy formation. This is powerful because we are able to find galaxies in the simulation

https://www.Illustris-project.org/

with asymmetrical HI spectra and instantly know the masses of their dark matter halos. Samples from Illustris can show us if there is a correlation of dark matter halo mass and HI asymmetry. Furthermore, Illustris holds capabilities to show the progression of asymmetries over time, which is impossible in observational studies. Illustris does hold some limitations, but we can still put ongoing theories to the test and get high-precision results.

Theory and Methodology

For this study, I created an asymmetry calculator that took Illustris data of sub-halos of various dark matter halo masses and calculated the asymmetry of the HI spectra. The time it takes to run varies for different galaxies, which was a limitation in building large samples. However, the code is capable of building large samples of galaxies at any specified redshift, across any mass range, and from any specified simulation (there are 18 simulations within IllustrisTNG). I focused on the simulation TNG100-1, halos at redshift $z = 0$, and within the $10^{11} - 10^{13.5} M_{\odot}$ range.

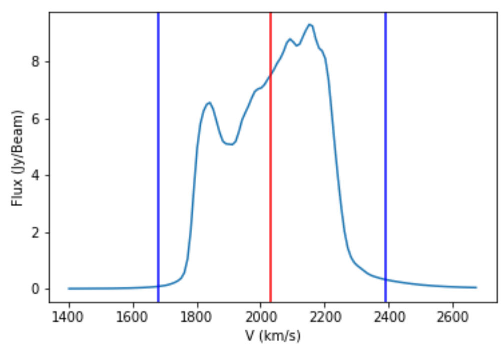

Fig. 1.— Full HI profile of simID = 'TNG100-1' subID = 385350 galaxy from Illustris. Red marker is the central velocity of the galaxy, which is what we define as the center of the HI profile. The blue lines are the lower and upper bounds of the flux plot as deffined by the asymmetry calculator. This sub-halo has an asymmetry of $A = 0.8$.

Figure 1 shows an HI profile from a specific sub-halo. My asymmetry calculator defines the central velocity of the sub-halo and the lower and upper bounds of the HI flux. I define asymmetry as $A = log_{10}(L/R) \quad 1$, where L is the blue shifted integrated flux (left of central velocity) and R is the red shifted integrated flux (right of central velocity).

I calculated the asymmetry of 1052 sub-halos of various masses, and used the IllustrisTNG catalogs to collect the halo mass (referring to the parent halo which may contain an entire galaxy group), sub-halo mass (single galaxy), primordial gas accretion rate, and metallicity. I then analyzed the relationship between asymmetry and these measurements to see if there are any meaningful trends with asymmetry within Illustris. By retrieving information on halos at different redshifts throughout the development of the simulation I could also see how the asymmetry of halos varied over time. I chose four different halos and plotted their asymmetry from redshift $z = 0$ until Illustris stopped recognizing the halo. This process was very time consuming so I will only present four halos and their asymmetries over time.

Results and Analysis

When getting data for the halos I made sure to have halos of varying mass. A large majority of halos are lower in mass; therefore, the data tend to be more dense at the lower mass bins. This causes some gaps in the data, however this is not a hindrance towards my analysis. The samples of halos in all mass ranges shown are representative.

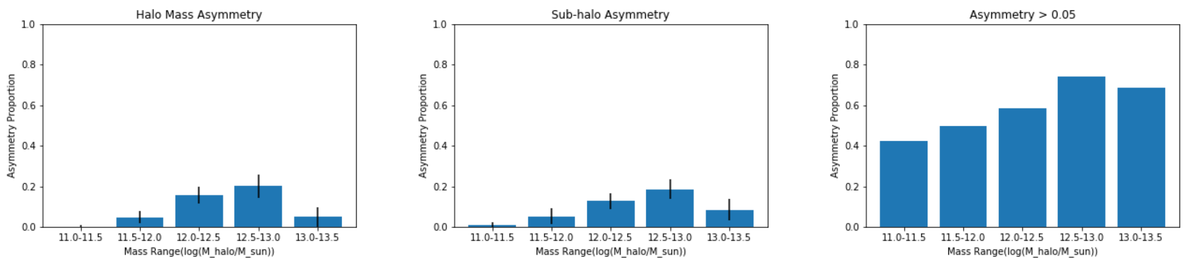

Fig. 2.— Proportion of halos that are significantly asymmetrical binned by mass. On the right is the proportion of halos that $0.95 < A > 1.05$.

The defined threshold for significant asymmetry is 1.5σ from average asymmetry (which is $A = 1$). The distribution incorporated the entire data set and resulted in $\sigma = 0.143$ in asymmetry value. Figure 2 shows how the proportion of significantly asymmetrical halos changed with halo mass and sub-halo mass. As expected, there is not much difference between halo and sub-halo mass ranges and their asymmetry, since halo mass and sub-halo mass are very closely related. There is an increase in asymmetry as mass increases, with a notable drop off at the $10^{13} - 10^{13.5} M_\odot$ range. Bournaud et al. (2005) defined asymmetry at $A > 1.05$ or $A < 0.95$ and found in their study that 63% of halos where asymmetrical. The third plot of figure 2 utilizes this same criteria, and we find that at different mass ranges we also find comparable asymmetry proportions.

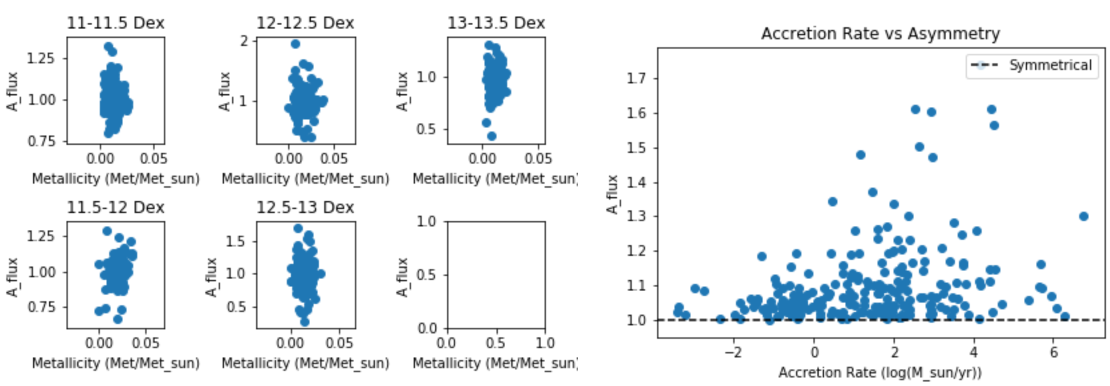

Fig. 3.— Asymmetry plotted against metallicity in different halo mass ranges. On the right is the asymmetry plotted against the primordial accretion rates of all halos with positive accretion rates in units of $M_\odot/Yr$.

The asymmetry-metallicity plots are binned by sub-halo mass to limit any correlation due to the mass-asymmetry relation. The plots were given Spearman correlation tests. Results of this test are on Table 1. The correlation values were all extremely low; there is no significant correlation between asymmetry and metallicity. The second plot of figure 3 shows the relationship in asymmetry in HI flux with the primordial accretion rate. This is the accretion rate at the exact time of observation, which is at the end of the simulation and at redshift $z = 0$. Results show that sub-halos tend to have more variance in asymmetry when they have higher accretion rates. We also see a drop off towards the higher accretion rates of the data, though this is likely due to having significantly less data in that mass range. This reflects our results from figure 2, since the sub-halo mass vs. accretion rate relationship has a positive correlation (at higher mass we also expect higher accretion rates).

Sub-halo Mass ($log_{10}(M/M_{\odot})$)	Correlation	P-value
11.0 – 11.5	−0.05	0.44
11.5 – 12.0	0.08	0.32
12.0 – 12.5	−0.00	0.96
13.0 – 13.5	0.05	0.58

Table 1: Spearman Correlation Test of Asymmetry-Metallicity

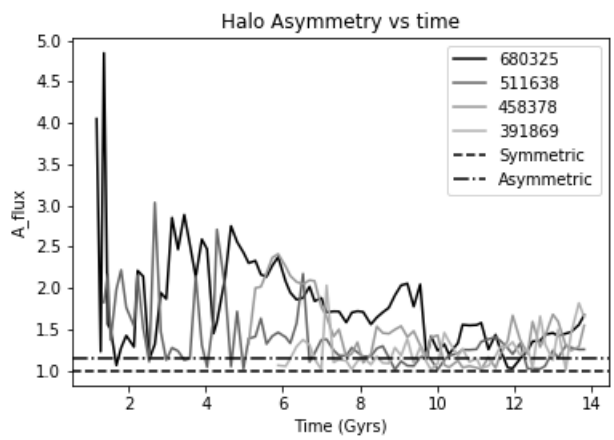

Fig. 4.— Asymmetry of a halos 680325, 511638, 458378, and 391869 over the time in which they were recognized as formed halos by Illustris.

Bournaud et al. (2005) shows how the asymmetry of halos changed over time in a simulation over the course of about $6Gyrs$. In figure 4 I show how asymmetry varied over the course of each halo's "lifetime". Illustris ran for about $13.8Gyrs$ in simulated time, which is where we started the calculation of asymmetry and worked backwards in time until Illustris could no longer identify the halo. Halos 680325 and 511638 were around a lot longer, and show how the early universe was much more chaotic. This corroborates current theories of our early universe, serving as more evidence of the level of realism of Illustris. This plot shows that IllustrisTNG can be used to track asymmetry over time, but more data are needed to draw conclusions from this analysis; and there is much more we can learn about galaxy formation from this simulation.

Conclusions

IllustrisTNG is a realistic large scale simulation that gives us many opportunities in understanding galaxy formation. I utilized it to study asymmetries in integrated HI flux of sub-halos of various masses. This gives us insight into the extent at which galaxies of different masses may be susceptible to being asymmetrical. I also collected accurate measurements of galaxies' metallicity and primordial accretion rates, which gave us insight into their relationship with HI asymmetry. My data suggest that there is no relationship with metallicity and that accretion rate, sub-halo mass, and halo mass all have a positive relationship with asymmetry. Although HI asymmetry may be associated with gas accretion, we do not find it to be inversely related to halo mass as expected based on previous simulations. By the end of this project, I was looking at how asymmetry changed over the course of the simulation, and noticed some interesting behavior in four specific halos over the course of their entire lifespans. This is not something that can be done with observations, since their lifespans range gigayears.

There are still many possibilities with this type of research and IllustrisTNG. There are 17 other simulations that I did not explore, and 96 other redshifts to study. Furthermore, the progression of HI asymmetry in halos over the course of their lifespans would be very interesting to study on a larger scale and across all other simulations.

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