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Evolution of Galaxy Size in the FOGGIE Simulations

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Abstract

Cosmological simulations are a powerful tool to study galaxy evolution as they can span a substantial fraction of the cosmic time. In this research note, we use the Figuring Out Gas and Galaxies In Enzo simulations—cosmological hydrodynamic simulation of Milky Way-like galaxies—to measure the evolution of the radius of the galaxy disk. Additionally, we analyze the simulations along three different lines of sight. Lastly, we show that the disk size increases over time regardless of angle of projection.

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1. Introduction

We present the evolution of the disk size of a simulated Milky Way-like galaxy. Additionally, we report on the effect of different lines of sight on said evolution. Studying gas in galaxies is important as it is raw material for star formation. The gas that forms the galaxy disk is of higher density than that outside the disk, i.e., the circumgalactic medium (CGM). CGM serves as a reservoir of gas for the star formation in the disk. The outward pressure from supernovae explosions and strong stellar winds push hot gas outwards into the CGM. This expelled gas sometimes falls back onto the galaxy disk upon cooling down, and may reignite star formation. Understanding the circulation of gas is important to better understand the star formation and the consequent galaxy evolution. In order to understand this process however, we first need to define the disk-CGM interface. Thus our research focuses on quantifying the extent of the disk, and disk size evolution over time. In this note, we first present the data analysis method we used, including Fixed Resolution Buffers (FRBs). We also present methods used for density gradient fitting, and lastly results and conclusions of our research.

2. Simulations

We use the Figuring Out Gas and Galaxies In Enzo (FOGGIE) simulations, which are based on the publicly available code Enzo. The FOGGIE simulations are zoom-in cosmological simulations in a 100Mpch^{-3} box (Simons et al. 2020). One of the features of Enzo is Adaptive Mesh Refinement (AMR). AMR focuses available computational resources in grids of interest that have more density, which enables more efficient use of limited computational resources. FOGGIE forces a minimum level of refinement in the region of interest. The zoom-in simulations are produced by setting a refine box around the center of a galaxy. The width of the box for "forced refinement" was set as 287.77ckpc (200h^{-1} comoving for h=0.695) (Lochhaas et al. 2023). The FOGGIE simulations include six galaxies that have been chosen to be similar to our Milky Way galaxy in two main criteria. First, galaxies that have similar virial masses to our Milky Way galaxy at redshift z=0. Second, galaxies that did not undergo any major merger in the past 10 billion years (z=2). For our research, a specific FOGGIE halo "Tempest" was chosen out of the six halos since it is the most studied FOGGIE halo.

3. Method

3.1. Fixed Resolution Buffer (FRB)

We use the FRB of yt software (Turk et al. 2011) to visualize the gas density in a 2D projection as viewed from three orthogonal axes of x, y, and z. It is important to note that "axes" refers to the cartesian axes defined with respect to the simulation box, not with respect to the galaxy itself. The FRB routine yields a uniform resolution image, based on a given input resolution. The advantage of FRB is that it enables us to project the simulated galaxy in a uniform grid, which mimics a real observation. We fix the resolution of the FRB to be 70 pixels across a side. This corresponds to a pixel size of 2.857 ckpc per pixel. To compensate for the expansion of the universe, the box size was set to 200 ckpc (=200/(1+ z)pkpc, where z denotes redshift). It is important to note that while a fixed comoving [ckpc] size was used for the FRB, the figure labels here denote the physical distance [pkpc], which varies with redshift.

3.2. Radial Density Profile

In Figure 1, we radially bin the projected density from the FRB image, and plot the mean density of each bin. To measure the disk size, we perform a piecewise linear fitting routine, which fits for an inputted number of piecewise segments and returns the turnover point. We bin the original FRB into bins 3 ckpc in width. The radial profile of the projected density exhibits a turnover in the slope at a certain radius. This is the extent of the galaxy disk, beyond which is the CGM. In order to quantify the size of the disk, i.e., the location of this turnover radius, we perform the piecewise fitting routine. The red line in the left panel of Figure 1 represents the binned mean gas density for each bin, and the blue lines are the best fit to the data obtained from the piecewise fitting algorithm. These blue segments represent different density gradients within and beyond the galaxy disk. This process was iterated over different redshifts and three lines of sight to show the growth of the galaxy disk over time and along different projections.

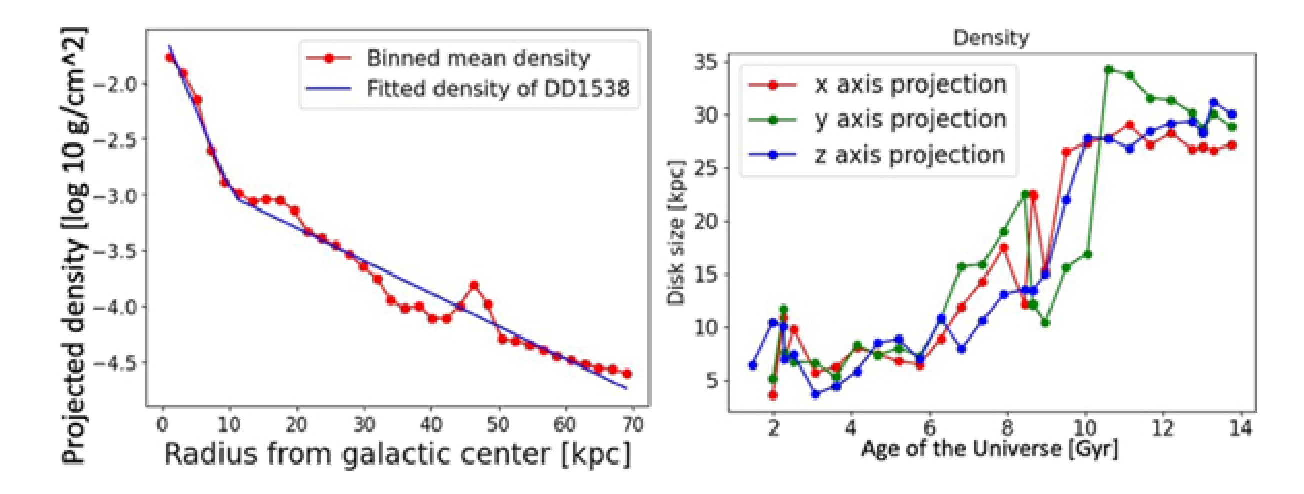

Figure 1. Left panel shows a radially binned density plot. The blue lines show the fitted lines obtained from the linear fitting algorithm. A turnover around 12kpc is clearly visible, which we defined as the size of the galaxy disk. Right panel shows the disk size changes in the galaxy "Tempest" from density analysis over time [Gyr]. Disk size changes in three different axes are projected.

4. Results

The right panel of Figure 1 shows the increase in disk size with time. The increase rate is not linear, as there is a relatively rapid growth between 6 and 10Gyr, then the growth slows down after 10Gyr. Since the disk size increase shows similar patterns for all three lines of sight, the axis of the simulation is irrelevant to the observed disk growth.

5. Discussion

We have quantified the change of the disk size in the simulated galaxy "Tempest." Examining disk size growth rate and its change over time provides deeper understanding about Milky Way-like galaxy evolution. We converted the 3D simulation data into a 2D projection so as to mimic observed data, i.e., a projection of the galaxy onto the plane of the sky, along only one line of sight. This ensures our results can be compared to observed galaxies too. Lastly, the fact that the axis of simulation was irrelevant to the disk growth might imply that the FOGGIE galaxies have fairly uniform circular disks, and thus we found the drop in density at the same radius regardless of direction of observation.

6. Conclusion

Using the FOGGIE simulations, we studied the evolution in the size of a Milky Way-like galaxy. From the analysis, we observed an increasing trend of the galaxy disk size over time. The growth of disk size was unaffected by the line of sight, and thus can be observed regardless of angle of projection. The rate of growth was nonlinear, as we observed relatively rapid growth in size around 6–10Gyr, which slowed down after 10–11 Gyr. Further analyzing the metallicity distribution in the galaxy plane would be a potential future research topic that could provide more insights on dynamics of CGM.

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