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M33's Future Density Profile and Star Formation Rate

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ABSTRACT

1. A sentence that defines your topic 2. A sentence that says why your topic is important 3. A sentence that says what question you are exploring 4. A sentence about why that question is important. 5. For each finding: A sentence that states what you found. 6. A concluding sentence(s) about what each finding means.

Keywords: Major Merger — Stellar Disk — Star Burst — Kennicutt-Schmidt Relation — Late Type Galaxy — Early Type Galaxy

1. INTRODUCTION

Our own Milky Way Galaxy is about to go through a major merger with the Andromeda galaxy (M31). A major merger is what occurs when two galaxies of relatively the same size collide. However, these two galaxies will not be the only ones whose physical properties will change due to the merger. M33, a late type (i.e. a spiral, gas rich) in our Local Group (Semczuk et al. (2018)), will also be changed forever once this collision occurs. The major question is how. Repeated tidal encounters could cause it to transformation into an early type (i.e. elliptical, gas poor) galaxy. After multiple close passes causing bursts in star formation, and therefore using up a large portion of the current gas mass, M33 could evolve into a gas poor spiral or elliptical once M31 and MW collide.

A galaxy is a system of stars, dust and gas that are gravitationally bound, with a central black hole. Galaxies have stars at each stage, but may not necessarily have gas if the galaxy is quenched. Willman & Strader (2012) define a galaxy to be a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons (i.e. gas and stars) and Newton's laws of gravity due to the presence of dark matter, which explains why everything is bound together. Galaxies evolve as their stars age and die, or they collide, or have a close encounter with another galaxy causing their structure and internal dynamics to change and gas mass to increase. The gas of a galaxy can be decreased due to star bursts or the black hole expelling gas. The environment the galaxy is moving through can play a major role in the gas content depletion. M33 is destined to have its gas content impacted by the major merger of M31 and the MW. It is unknown, however, how the star formation rate of M33 will be effected, and how long its current gas content will last once a burst in star formation is initiated. By studying this, we can better understand how a satellite galaxy is impacted by a major merger, and how a late type galaxy can be transformed to an early type galaxy.

Semczuk et al. (2018) have studied the possibility of a past interaction between M33 and M31 where they got to within 37 kpc of each other. Bekki (2008) provide evidence that the two galaxies did interact in the past hinted at by the bridge like structure between the two . It has been proposed that the interaction occurred 4-8 Gyr ago, and is the reason M33 has a warped HI region. This gaseous warp is thought to be due to the tidal forces and ram pressure from M31. However, more recent studies such as Patel et al. (2017) discuss that M33 is on its first pass around its host, and that it is highly unlikely M33 has gotten within 100 kpc of M31 in the last 3 Gyr. These results show that the gaseous warp is not due to any interactions. Past and future interactions are summarized by Figure 1.

One hypothesis to better understand the exact manner through which late type galaxies transform to early type galaxies is tidal stirring. Tidal stirring can be tested to see if it actually transforms a galaxy by modeling the tidal evolution of M33 once it enters the tidal field of the MW and M31 combined system. Łokas et al. (2015) has done

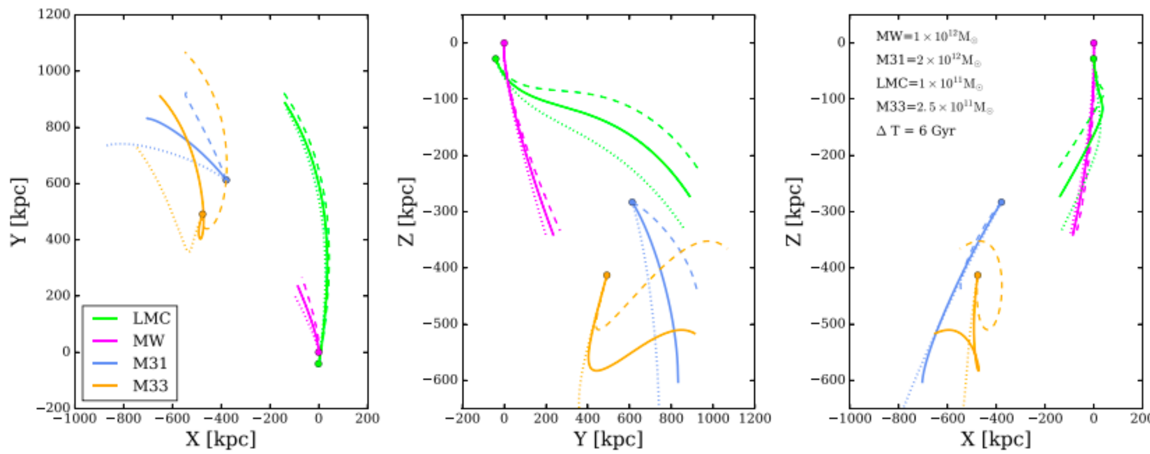


Figure 1: Patel et al. (2017) plot shows the numerically integrated orbital trajectories of our Local Group for the last 6 Gyr. These positions are plotted with respect to MW's position as a function of time. Different line types of solid, dashed and dotted represent resulting orbits for the mean velocity vectors, a -1σ and a $+1\sigma$ respectively.

simulations for tidal stirring of disk galaxies orbiting a Milky Way like host. It is believed that this leads to dwarf spheroidal galaxies, and is dependent on a resonance between the angular velocity of the stars in the dwarf and its orbital motion. Because of this resonance, tidal stirring has occurred.

Another reason it is believed M31 and M33 collided is because they both experienced a burst in their star formation rates (SFR). Bernard et al. (2012) has studied through simulations that when two galaxies have a close encounter, a burst in SFR occurs. When the interaction is believed to have occurred, the SFR density of M33 was approximately three times larger than its normal density, putting it at $0.6 \times 10^{-9} M_{\odot} yr^{-1} pc^{-2}$. Since these previous studies have shown that SF can be induced from interactions, it is highly probable that M33 will undergo another star burst when exposed to much more severe tidal interactions as the MW and M31 merge. These star bursts use up a large amount of gas, which will decrease the gas content and help transition M33 from the blue sequence to the red sequence. This will help gain a better understanding of how a gas rich late type spiral can evolve into a gas poor spiral or elliptical.

2. THIS PROJECT

The goal of this study is to better understand how a gas rich, late type spiral can be transformed when exposed to extreme tidal interactions such as those that come from a close encounter with a major merger. This paper will address the correlations between a surface density profile and a gas surface density profile. It will explain how a gas surface density profile can be used to determine when a galaxy will run out of gas based on its SFR.

Specifically, this paper will determine when M33 will use up its gas once M31 and the MW have collided. This will shed light on how, if it does, a galaxy such as M33 can become an early type spiral or elliptical galaxy.

There is limited knowledge on how a major merger impacts its satellite galaxies and vica versa since M33's total mass is a significant fraction of its host's. This means that the satellite can affect the dynamics of its host. How M33's dynamics and gas content will change for each close pass of M31+MW system will shed light on the survivability of an M33-like system in the presence of a massive host system like M31+MW.

3. METHODOLOGY

N-body simulations are useful for astrophysics because they allow us to model dynamical systems with a few bodies, and apply that to much larger scales. Specifically for galaxies, they are useful for better understanding the evolution. Fascinating simulations have been done by van der Marel et al. (2012) on the fate of our Local Group using Monte Carlo simulations. From these, it was found that, most likely, the MW and M31 will merge first, and M33's orbit will eventually decay into them. However, there are two other possibilities that have been investigated. The first, is that there is a very small probability of 9% that M33 would actually collide with the MW first when it reaches its first pericenter. The second is only a 7% probability, but it is that M33 will be ejected from the Local Group all together. This paper uses the same data that was used for those Monte Carlo simulations. It gives the position components in kpc and the velocity components, both measured from the center of mass position of the MW. It also give the time in units of Myr, total number of particles, particle type (i.e. dark matter, disk stars and bulge stars) and the mass of the particles in $10^{10} M_{\odot}$.

Putman et al. (2009) report that M33's current SFR is $\sim 0.7 M_{\odot} yr^{-1}$. They also state that based on M33's HI mass and current sources of fuel, it only has 2 Gyr left of star formation. The entire galaxy has a gas mass of $2.38 \times 10^{9} M_{\odot}$ based on the largest distance of 964 kpc. Furthermore, it is predict that M33 will become fuel for M31 by providing $\sim 25\%$ of M31's current HI mass.

In order to determine how the SFR of M33 will change over time, and how this changes the structure of M33, we have first determined a ratio between the gas mass and stellar mass. Based on results from Homework 3, the disk mass of M33 is $0.009 \times 10^{12} M_{\odot}$ making the ratio of gas to stars 0.264. This ratio will be used to translate a plot of the surface density of stars in M33 to a gas surface density. Using the Kennicutt- Shmidt relation from Kennicutt (1998),

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} (\frac{\Sigma_{gas}}{1 M_{sun} pc^{-2}})^{1.4 \pm 0.15} M_{\odot} yr^{-1} kpc^{-2}, \tag{1}$$

where Σ_{gas} is the surface density of gas, the gas density can be turned into a SFR density, Σ_{SFR} by multiplying it by the area of M33.

In order to determine when the gas of M33 would be used up by, we use the SFR at each point in the orbit to decrease the gas mass at each point in time. This graph would look similar to that given by Semczuk et al. (2018) in Figure 2 and we will mark down every position in the orbit where M33 gets really close to M31/MW, and use that to

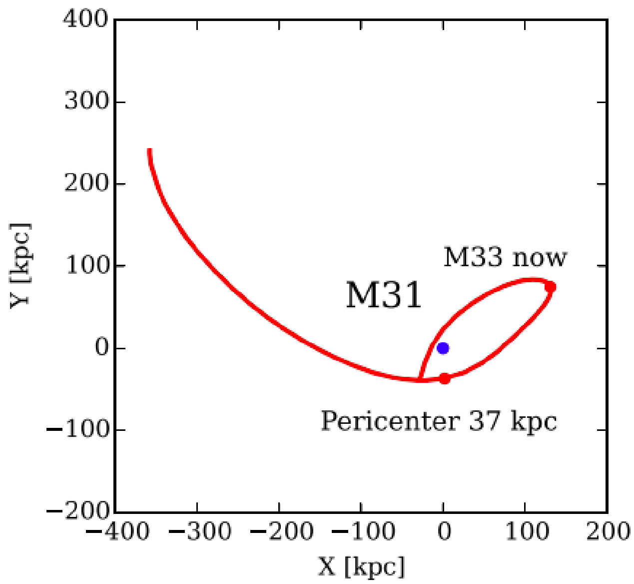


Figure 2: Projection of M33's orbit done by Semczuk et al. (2018)

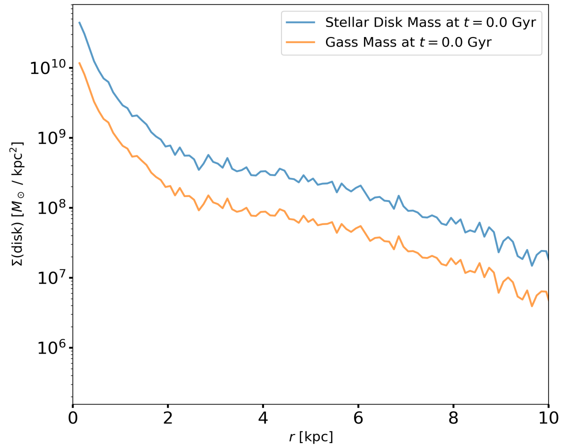
indicate where a burst of star formation is expected.

We expect there to be an increase in the SFR because of the collision of M31 and MW. As discussed, when galaxies get close together, we can expect there to be a star formation burst. As for the structure of M33, it could very well become an early type due to the depletion of its gas supply within a few Gyrs after the initial collision.

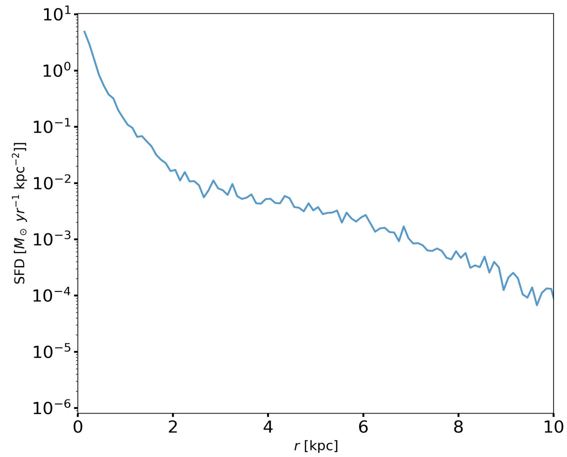
4. RESULTS

Figure 3 shows how various quantities change with radius. Plotted is the the current stellar disk density, gas density, star formation density and finally star formation rate all as a function of radius. The results are as expected and agree relatively well with Bernard et al. (2012). Both the SFD and SFR decrease as a function of radius, which makes sense considering there is less mass at the outermost radius.

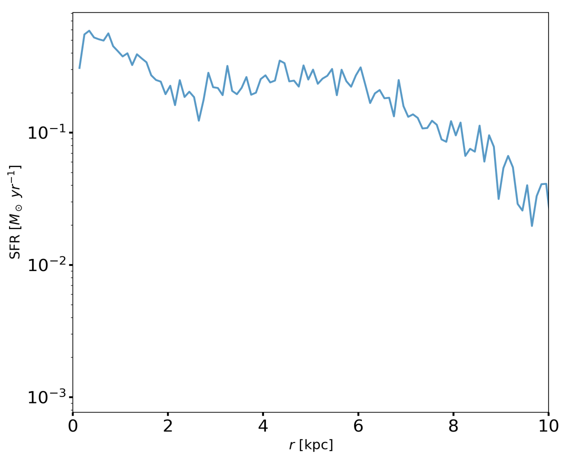
Next, we plot the stellar disk density, gas density, SFD and SFR as a function of time. We do this by taking each snapshot given in the data from Patel et al. (2017). We convert each snapshot to time, and plot that as the x-axis. It is clear that there are fluctuations in the densities and thus the SFR.



(a) Stellar disk density and gas density at snapshot 0. This shows how the stellar disk density and gas density both decrease with radius and snapshot.



(b) Star formation density versus radius where a decrease in density is apparent at larger radii.



(c) Star formation rate versus radius. Showing a downward trend as the outskirts of the disk are reached.

Figure 3: The above images show how things are at current time. Each show the same trend that the densities and therefore the SFR decrease with radius.

We mark on the plot where close encounters with M31 occur. These close encounters were determined based on the plot given by Figure 4. It is obvious that M33 and M31 have 6 close encounters within the next 12 Gyr, which means we would expect to see a burst in the SFR at those times. The time and separation of these collisions are given in Table 1.

Time [Gyr]	0.929	4.286	6.714	8.286	9.571	10.571
Separation [kpc]	79.78068125	55.90542192	47.593031	42.89399725	36.47438279	35.15931313

Table 1: M33-M31 times (given in Gyr) and positions (given in kpc) of the six close encounters represented by the minimums in Figure 4

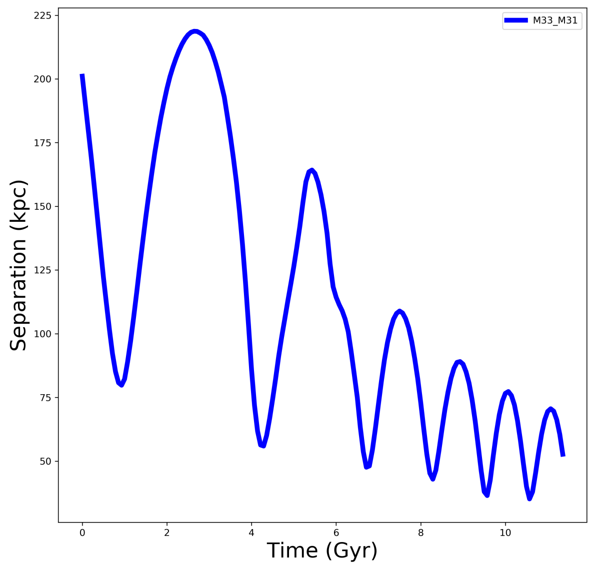


Figure 4: Relative position of M33 with respect to M33. The close encounters are shown by the minimum. These points are where we would expect an increase in the SFR.

The most important results of this study are summarized in Figure 5, which shows how the densities and SFR change with time. The plots are annotated with where there was a close encounter based on Figure 4. (Since they're super wrong right now, I'll finish this section once the plots are correct) There are three peaks in the SFR where there are three close encounters between 8 and 12 Gyrs.

5. DISCUSSION

Given the results presented above, it is apparent that the SFR increases with time, and the gas density decreases. These results support my hypothesis that the SFR will increase as M33 gradually falls in towards the M31+MW system. Since stars are being formed at an increased rate, the gas density will therefore decrease, and M33 will eventually run out of gas, but not until after at least 12 Gyr.

Putman et al. (2009) simulations show that a burst in star formation occurs due to a close encounter. They also cite the SFD to be $0.6 \times 10^{-9} M_{\odot}\, yr^{-1}\, pc^{-2}$, which our plots get close to at the outer radius, but do not quite reach. Bernard et al. (2012) report M33's current SFR to be $\sim 0.7\, M_{\odot}\, yr^{-1}$.

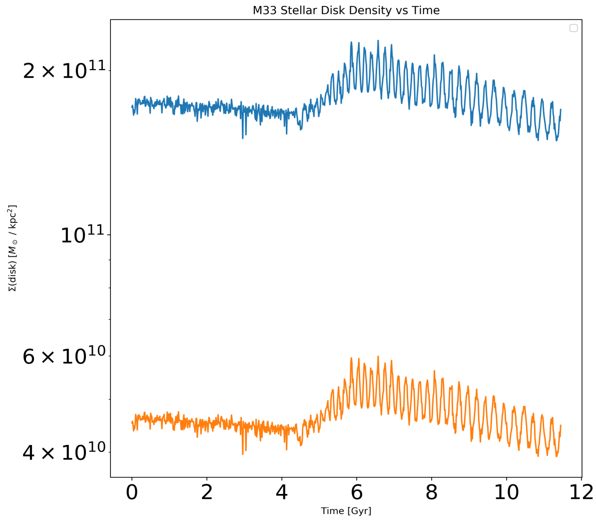
6. CONCLUSIONS

Through this study we can "watch" a late type spiral lose its gas, and thus change form. We plot the shape of the galaxy at current time, and at 12 Gyr from now. Through these images presented in Figure 6, we see that M33 maintains its spiral shape. Combing these results and the results of the gas density profile, we conclude that M33 does indeed evolved into a gas poor spiral as it has more close encounters with M31/MW causing star formation bursts to eat up a significant portion of its gas reservoir.

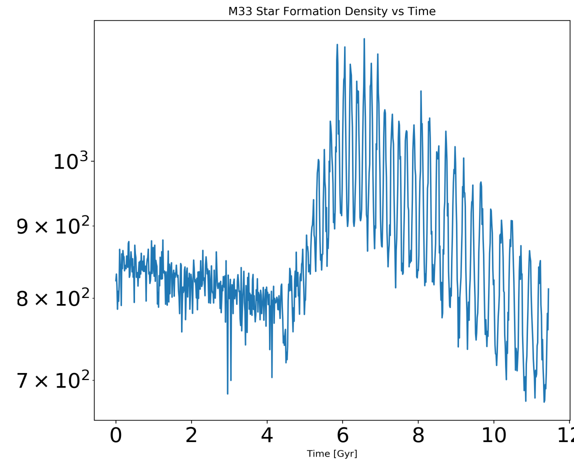
1. Paragraph 1: Summarize your introduction - basically lines (1-4) of the abstract. 2. Paragraph 2: Highlight one key finding, what it means and whether this agreed or disagreed with your hypothesis. Add more paragraphs per finding. 3. Last Paragraph: Comment on future directions - what other things could you do to explore the topic further? Or to improve your code?

7. ACKNOWLEDGEMENTS

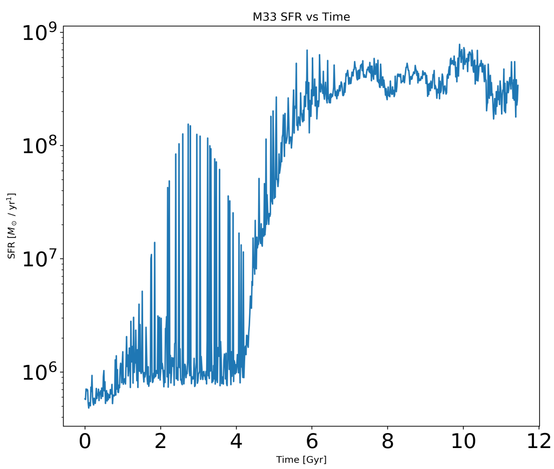
1. Astropy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018 doi: 10.3847/1538- 3881/aabc4f) 2. matplotlib Hunter (2007),DOI: 10.1109/MCSE.2007.55 3. numpy van der Walt et al. (2011), DOI : 10.1109/MCSE.2011.37 4. scipy Jones et al. (2001),Open source scienti



(a) Stellar disk density and gas density at throughout the snapshots.



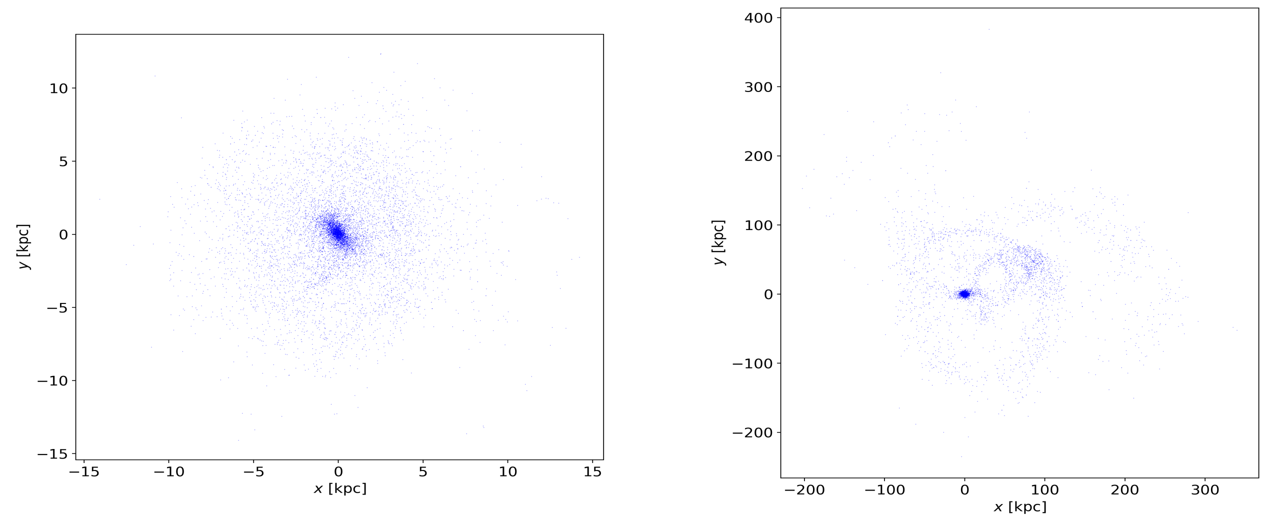
(b) Star formation density versus time.



(c) Star formation rate versus time. Showing a downward trend as the outskirts of the disk are reached.

Figure 5: The above images show how things change as a function of snapshot, where snapshot was converted to Gyr. Obviously, these graphs are currently wrong, but I'm working on fixing them.

c tools for Python. http://www.scipy.org/ 5. ipython Perez Granger (2007), DOI : 10.1109/MCSE.2007.53



(a) M33's current shape at snapshot 0.

(b) M33's shape at snapshot 801, or about 12 Gyr from now.

Figure 6: The above images show how M33 evolves. 6a shows what M33 currently looks like. 6b shows what it will look like in about 12 Gyr. Clearly it has become much more scattered and much smaller. These changes in its shape are primarily due to the close encounters it went through with M31+MW. (could put in an image of it at each snapshot when there was a close encounter)

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