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SOME LIKE IT HOT: TOURING THE CGM OF SIMULATED MILKY WAY TYPE GALAXIES

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ABSTRACT

The CGM is where most of the gas mass of galaxies lay [CITE]. It is important to examine the evolution of the CGM and see how changes in the galaxy may effect this large reservoir of gas as it has direct consequences on the continued evolution of the galaxy. We examine a suite of genetically modified Milky Way-mass galaxies to pin point the effects on the CGM that small and large scale changes to a galaxy may cause. By determining what modifications to a Milky Way-type simulated galaxy results in the most MW like galaxy and furthermore examining what characterizes the CGM of that galaxy, we take a step closer to better understanding the elusive CGM of our own galaxy.

Subject headings: Gas physics – Galaxies: circumgalactic medium – Galaxies: spiral – Galaxies: kinematics and dynamics – Methods: Numerical

1. INTRODUCTION

Since 2011, the circumgalactic medium (CGM) has emerged as one of the final, unexplored frontiers for understanding galaxy evolution in the low-z universe. Understanding its phase structure, dynamics, and overall relationship to its host galaxy is now of critical importance to making progress. The CGM is a gaseous halo surrounding a galaxy through which incoming gas passes as it flows from the intergalactic medium onto galaxy disks. While the CGM hosts some of the most observationally elusive particles in the universe, studies of this medium suggest that it is multi-phase, highly dynamic, and dominated by complex ionization processes [CITE]. The CGM also maintains a reservoir of gas that is simultaneously being accreted onto the galactic disk and outflowing from the galaxy through stellar and supermassive black hole (SMBH) feedback [CITE, Michael, Fabio, Jillian]. This recycling of gas into and out of the galaxy serves to both fuel the galaxys star formation and to quench its activity. It is clear that the CGM plays a pivotal role in the formation and evolution of its host galaxy [CITE]; however, there are many questions about the CGM that continue to elude astronomers. Such as, how does baryonic content and ionization state depend on the activity of the galaxy host, particularly SMBH feedback? And also, how does baryonic content and ionization state depend on galaxy assembly history?

Related to the mysteries posed by the CGM, astronomers are also trying to understand how the quenching of galaxies, that is the "turning off" of star formation that leads to red elliptical galaxies, occurs. In particular, what causes galaxies to quench, and what sustains their lack of star formation? Some considerations of this dilemma include staunching IGM accretion which feeds the CG[cite, observations and sims!] and effects which keep the CGM hot enough that stars are unable to form, such stellar or AGN feedback or *major?* mergers with other galaxies [Pontzen2017, cite more].

Observationally, one common method of investigating the CGM is through line of sight observations of background QSOs. Studying the spectra of bright

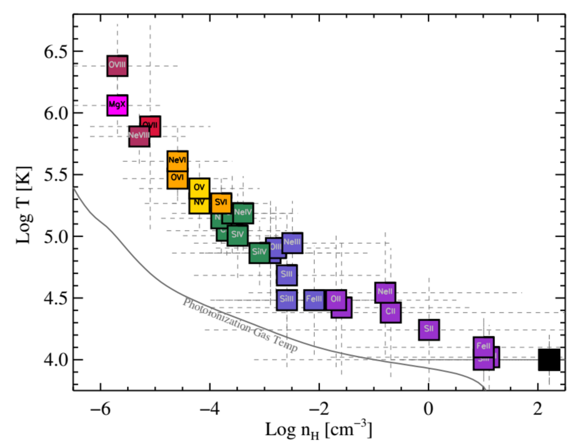

Fig. 1.— .

background objects allows us to examine the absorption features of the extended foreground gaseous media (including the CGM of galaxies nearby in projection) through which the QSOs light filters [FIGURE?]. These absorption-line studies allow for the direct measurement of absorption features (characterizing the CGM) within the QSO spectra, allowing us to study the elusive CGM more directly.

Cosmological hydrodynamic simulations are an important tool for understanding the underlying physics characterizing the CGM. Current smooth particle hydrodynamic (SPH) simulations utilize a dark-matter-only component and a follow-up zoom-in simulation to bridge the gap between large-scale galactic gravitational effect and the small-scale effects of gas, stars, and dust. Significant discoveries have already been made by investigating the CGM of simulated galaxies. Ford et al. (2013) determined that 65 − 80 percent of the total baryon mass of a galaxy exists in the halo outside the stellar disk and that ∼80% of the fuel for star formation in the Milky Way Galaxy was in the CGM 1 billion years ago. However, most comparisons between simulation and data have primarily focused on bulk column density comparisons and largely ignored gas kinematics

One of the most high resolution and recent cosmological simulation codes, ChaNGA, is a smoothed-particle hydrodynamics (SPH) code, which can directly examine the dynamics of the CGM in its simulated galaxies. Though comparable to the Eris simulations in mass and force resolution, ChaNGa has higher reliability when resolving high-density regions (Zolotov2012) and an improved implementation of black hole (BH) accretion, dynamics, and formation (Tremmel2016). These simulations allow us to determine kinematic information about the gas and metals residing in the CGM of these simulated galaxies and how it is affected by the BH and AGN activity.

[Describe genetic modifications galaxies "Small modifications to the initial conditions etc"]

These genetically modified (GM) simulations of low redshift galaxies keep the large scale structure and cosmological conditions of α CDM consistent, while allowing for modifications of their accretion histories (Roth2015, more?). The analyses of these GM simulations allow for direct comparisons of the CGM of multiple versions of the same galaxy in a physically self-consistent treatment. Previous studies have inspected the quenching mechanisms that arise from these varied accretion histories (Pontzen et al. 2017); however, they have not yet examined the dynamical effects on the CGM gas that these modified accretion histories generate.

These genetically modified galaxies serve to further examine the questions posed by the CGM and its relation to quenching. We can look to the changes or similarities in the CGM amidst this suite of simulations to see how the subtle changes made to each of these Milky Way galaxies affect the CGM in a self-consistent way.

The simulation parameters of the individual GM galaxies are described in Section 2. Simulation analysis methods are described in Section 3. Results are compiled in Section 4, and we summarize our findings in Section 5.

2. SIMULATION PARAMETERS

TABLE 1
Gas+BH Simulation Details

Sim	Total Halo Mass ($M_\odot$)	R_{vir} (kpc)
P0	9.91×10^{11}	262.3
GM1	1.02×10^{12}	264.5
GM4	8.58×10^{11}	250.0
GM5	9.08×10^{11}	254.7
GM6	7.58×10^{11}	239.8

2.1. *Patient 0 - h243*

At z = 0, our "Patient 0" (hereafter P0) of the galaxy simulation h243 has a final main halo mass of $\sim 1.07 \times 10^{12}$, virial radius of 269 kpc, and total gas and stellar masses of 1.09×10^{11} and 5.71×10^{10}, respectively (Table 2). We isolate the CGM as all the particles within the virial radius after removing the gas and stars within the main halo's disk (10 kpc radially and 4 kpc vertically). The CGM contains a total gas mass of 1.02×10^{11} and total stellar mass of 7.99×10^{9}.

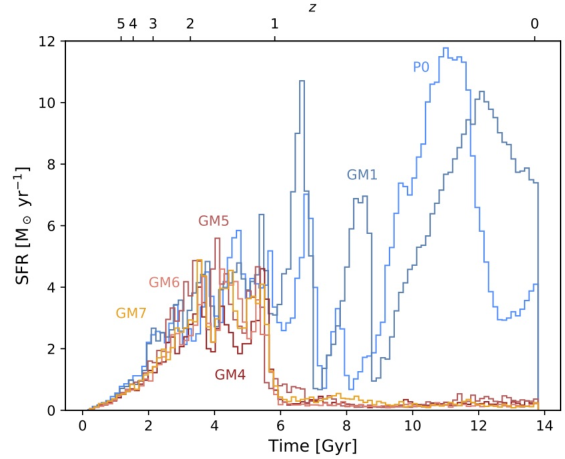

Fig. 2.— STUFF

The largest satellite of P0, which we genetically modify in following simulations, has a halo mass of [SAT MASS] at z [REDSHIFT of 1739], prior to the merger. The satellite enters the main halo at z = [redshift of MERGER] and has a final, z=0 mass of [SAT MASS at z=0].

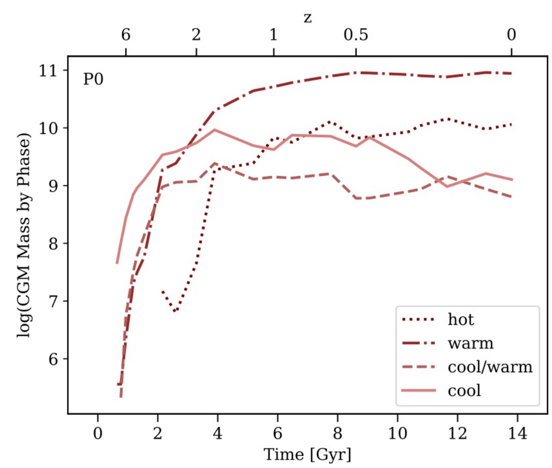

Fig. 3.— STUFF

[ADD SOME STELLAR DENSITY IMAGES? TO SEE DISK in P0/GM1 and to highlight lack of disk in GM4-6]

2.2. *GM 1 - Shrunk main satellite prior to merger*

Our first genetically modified galaxy (GM1) has the following modification: the mass of the main satellite halo of P0 was decreased to [SAT MASS AT z=1] at z = 1, prior to entering the main halo. The satellite enters the main halo at z = [redshift of MERGER] and has a final, z=0 mass of [SAT MASS at z=0].

At z = 0, GM1's main halo has a final mass of $\sim 1.07 \times 10^{12}$ (nearly the same as P0), a virial radius of 269 kpc, and total gas and stellar masses of 1.01×10^{11} and 6.43×10^{10}, respectively (Table 2).

Thorough description. Include satellite at z=0 and mass at z=0 and number of mergers and merger ratios, and total CGM mass and total disk mass in gas and stars. Make a table???

TABLE 2
Gas+BH Simulation Details

Sim	Total Halo Mass ($M_\odot$)	Total Gas Mass ($M_\odot$)	Total Stellar Mass ($M_\odot$)	CGM Gas Mass ($M_\odot$)	R_{vir} (kpc)	T_{vir} (K)
P0	1.07×10^{12}	1.09×10^{11}	5.71×10^{10}	1.02×10^{11}	268.9	5.12×10^{5}
GM1	1.07×10^{12}	1.01×10^{11}	6.43×10^{10}	9.18×10^{10}	269.2	5.12×10^{5}
GM4	7.76×10^{11}	6.36×10^{10}	1.04×10^{10}	6.35×10^{10}	241.7	4.14×10^{5}
GM5	8.93×10^{11}	9.11×10^{10}	1.41×10^{10}	9.09×10^{10}	253.3	4.54×10^{5}
GM6	6.81×10^{11}	5.77×10^{10}	1.13×10^{10}	5.75×10^{10}	231.4	3.79×10^{5}

2.3. *GM2 and GM3*

Our second (GM2) and third simulations (GM3) had similar genetic modifications which shrunk the mass of main satellite at z = 1. The satellite masses at z = 1 were [GM2 SATELLITE MASS] and [GM3 SATELLITE MASS] for GM2 and GM3, respectively. However, the modifications in both of these simulations resulted in satellites which fracture after they enter the main halo and don't surviving to z = 0. Due to the fracturing of the satellite halos, we didn't continue our investigations of these halos.

2.4. *GM 4 - Quenched!*

Our fourth genetically modified simulation (GM4) similarly modified the incoming satellite halo mass at z = 1, shrinking it to a smaller mass than GM1 but not as small at that of GM2. The satellite halo mass of GM4 is [GM4 SAT MASS] at z = 1, enters the main halo at z = [redshift of MERGER], and a final, z = 0 mass of [SAT MASS at z=0].

Interestingly, we found that at this level of modification, the main halo eventually ends up quenching rather than resulting in a Milky Way-type spiral galaxy as in P0.

2.5. *GM 5 - Quenched! More massive*

2.6. *GM 6 - Quenched! Less massive*

3. SIMULATION ANALYSIS

3.1. *P0, GM1, GM4 - Modified Satellite Halo Masses*

3.2. *GM4, GM5, GM6 - Modified Main Halo Masses*

4. RESULTS

Figure 5 shows the mass profile of two different phases of CGM gas as a function of radius for all five genetically modified galaxies and P0. The top plot in each subplot includes the mass profile for gas at temperatures between 10^5 and $10^{5.7}$ and lower plots include CGM gas between $10^{5.7}$ and 10^6 Each line on the plot represents a different redshift (see the legend for details). We call your attention to the dark-red, dashed line in each plot, which represents the mass profile of gas at z=0. In both the star forming galaxies, P0 and GM1, we note a large amount of gas between 10 - 25 kpc (note again that CGM gas is defined as gas outside of 10 kpc radially and 4 kpc vertically); however, between about 25-50 kpc there is a distinct lack of gas at this lower temperature phase. This large amount of close-in gas with a dropout slightly farther from the center of the galaxy is distinct from the mass profile of the quenched galaxies. The quenched galaxies – GM4, GM5, GM6 – all display a significant lack of this gas phase within about 50 kpc.

However, besides this slight difference in their mass profiles, the CGM in the quenched galaxies don't appear to have significant differences. Surprisingly, the mass profiles and comparisons of gas phases between these galaxies are not significant. Their phase diagrams also lack significant difference in their overall morphology, except in the distinguish where more gas is clearly present in the higher mass galaxies. Therefore, we surmise that the difference in the CGM are less motivated by the quenching of a galaxy but rather these differences are primarily driven by the virial temperature of the galaxy.

These results are consistent with Oppenheimer et. al. 2016 who used a suite of EAGLE simulated galaxies and found a bimodality to the OVI column densities in star forming and quenched galaxies. They argue that the star forming galaxies (10^{11} - 10^{12}), which were found to have a higher fraction of OVI, were at the right virial temperature to maximize OVI production, while their quenched galaxies (10^{12} - 10^{13}) had high enough virial temperatures such that the dominant ionization state was not OVI but rather OVII or above. Oppenheimer et. al. 2016 argues that the OVI content was not a tracer of star formation directly, but rather a more direct thermometer for the temperature of the halo.

We find this same results 6, higher OVI column densities in the star forming galaxies, in our suite of genetically modified simulations. However, it is important to note that our quenched galaxies are smaller in mass that our star forming galaxies. However, we find that our results are still consistent with those of Oppenheimer et. al. 2016, since the virial temperature of these smaller quenched galaxies are *lower* than the optimal temperature for OVI ionization (Table 2). We determine that the OVI still provides a direct thermometer for the temperature of the halo, which results in our consistent result of higher OVI column densities in our star forming galaxies despite the differences in mass between Oppenheimer et. al. 2016 and our own quenched galaxies.

5. CONCLUSION

Acknowledge some cool peeps.

REFERENCES

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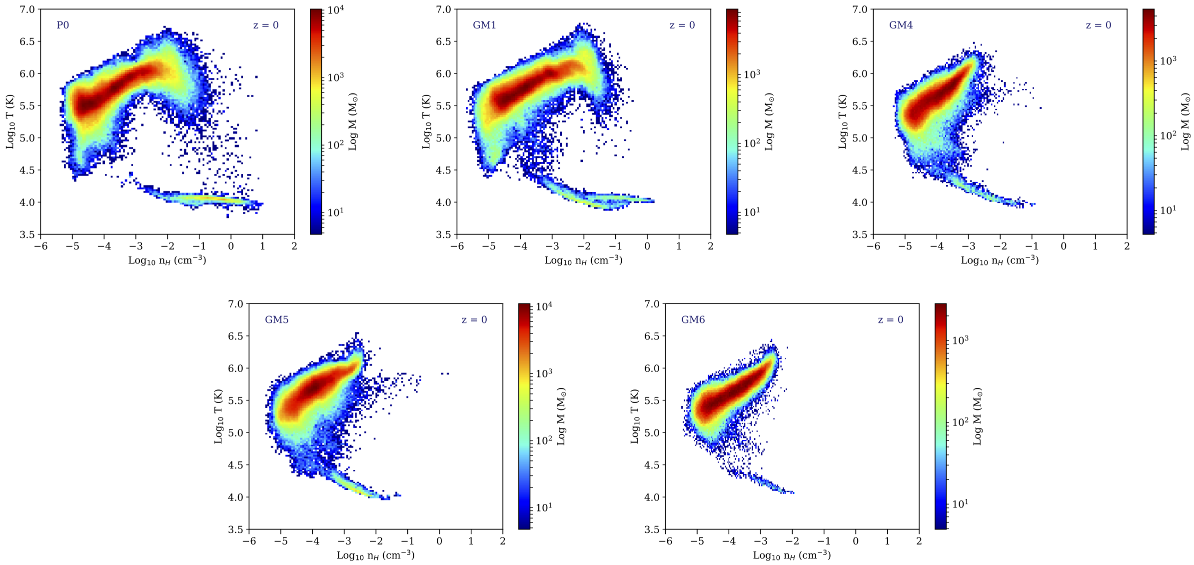

FIG. 4.— Phase diagram for the CGM of all our simulated and genetically modified galaxies. Isolated CGM as gas within the main halo that was outside the disk, defined out to a radius of 10 kpc and vertically to 4 kpc above and below the disk plane.

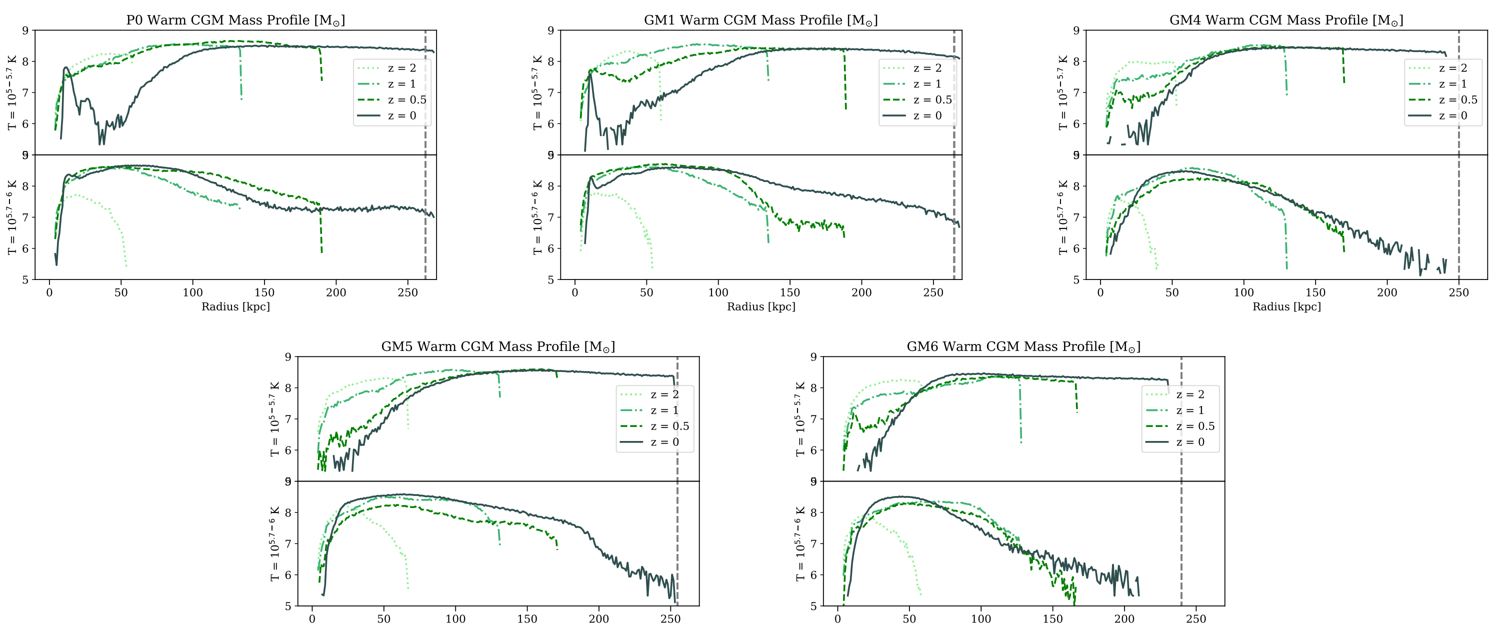

FIG. 5.— Mass profiles of the Warm CGM in our simulations suite of galaxies. The vertical grey, dashed line indicated the virial radius for each galaxy.

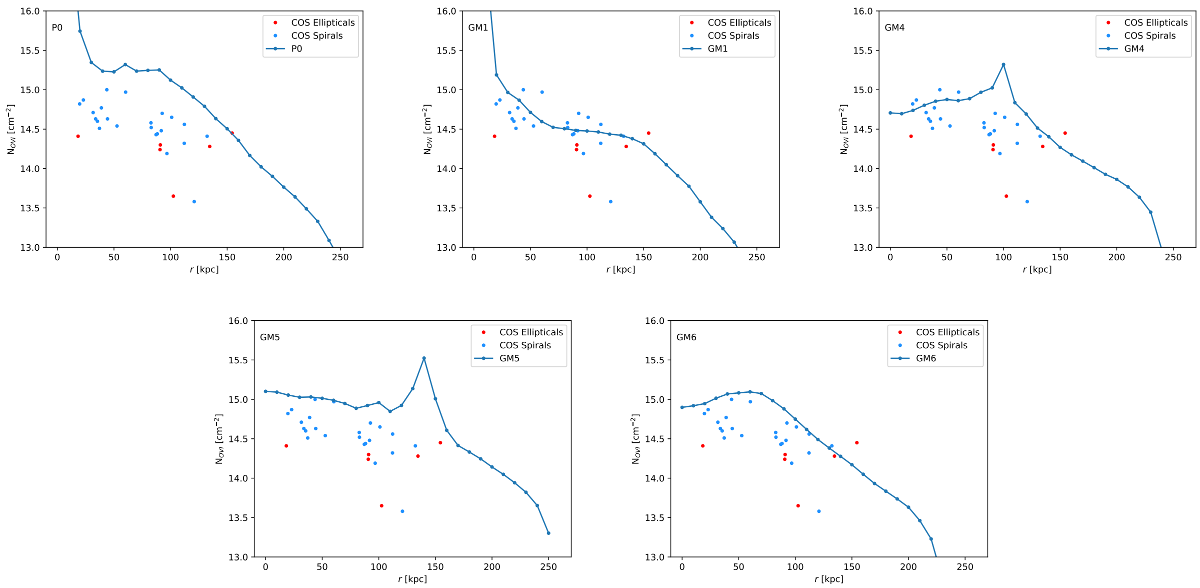

FIG. 6.— OVI Column Densities for our genetically modified galaxies. The OVI Column Densities of 27 COS Halo galaxies, ellipticals in red and spirals in blue, are overlaid.