Formation of a Malin 1 analogue in IllustrisTNG by stimulated accretion

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ABSTRACT

The galaxy Malin 1 contains the largest stellar disk known but the formation mechanism of this structure has been elusive. In this paper, we report a Malin 1 analogue in the 100 Mpc IllustrisTNG simulation and describe its formation history. At redshift zero, this massive galaxy, having a maximum circular velocity $V_{\text{max}}$ of 430 km s$^{-1}$, contains a 100 kpc gas/stellar disk with morphology similar to Malin 1. The simulated galaxy reproduces well many observed features of Malin 1’s vast disk, including its stellar ages, metallicities, and gas rotation curve. We trace the extended disk back in time and find that a large fraction of the cold gas at redshift zero originated from the cooling of hot halo gas, triggered by the merger of a pair of intruding galaxies. Our finding provides a novel way to form large galaxy disks as extreme as Malin 1 within the current galaxy formation framework.

Key words: galaxies:individual: Malin 1 – galaxies: formation – galaxies: evolution – methods: numerical

1 INTRODUCTION

Malin 1, discovered by Bothun et al. (1987), has one of the largest stellar disks known. With a diameter of at least 200 kpc, its angular size on the sky is wider than one arcmin even though Malin 1 is a quite distant object ($z \sim 0.09$). Malin 1 is a prime example of giant low surface brightness (GLSB) galaxies, characterized by their extended low surface brightness disk and high gas content (Sprayberry et al. 1995). Other examples of extreme GLSB galaxies exist (e.g. UGC1382, Hagen et al. 2016) with properties similar to Malin 1. Without the extended outer disks, Malin 1 and UGC1382 would otherwise appear similar to normal massive galaxies (Barth 2007; Hagen et al. 2016).

Observations of the Malin 1 disk are still limited due to its low surface brightness. Recent observations by Boissier et al. (2016) show spectacular spiral structure made of relatively young ($\sim 0.1–3$ Gyr) stars with metallicities between $0.1 – 1 Z_\odot$ with no apparent stellar age gradient across the disk. A more surprising feature is the large mass with $V_{\text{max}}$ above 400 km s$^{-1}$ if the (poorly constrained) inclination is low (consistent with, e.g., Galaz et al. 2015).

It remains a great challenge to understand the physical process behind a disk that is at least five times larger than the Milky Way. This single object, being an extreme outlier, is a severe test for the
current theory of galaxy formation and modified gravity (Lelli et al. 2010; Boissier et al. 2016). In this Letter, we report a Malin 1 analogue from the IllustrisTNG simulations. At $z = 0$, this galaxy has an extended gas/stellar disk with size/morphology similar to Malin 1. We then trace the extended disk back in time and find that a large fraction of the neutral gas came from the cooling of hot halo gas, triggered by a merger event involving a pair of intruding galaxies, a process we term ‘stimulated accretion’. In what follows, we first describe our methods and present our main results in Section 2. We discuss our findings and present observational tests in Section 3 and conclude in Section 4.

2 METHODS AND RESULTS

We identified this galaxy during our search for GLSB galaxies (Zhu et. al, in prep) in the IllustrisTNG simulation suite (Naiman et al. 2018; Nelson et al. 2018; Springel et al. 2018; Pillepich et al. 2018a; Marinacci et al. 2017b). The IllustrisTNG simulations build on the original Illustris project through a series of numerical and physical model improvements (Weinberger et al. 2017; Pillepich et al. 2018b) over the original Illustris model (Vogelsberger et al. 2014a,b; Genel et al. 2014; Sijacki et al. 2015). In this work, we use the TNG100 simulation which involves a box of side length $\sim 100$ Mpc as the original Illustris simulation. The baryon mass resolution is $1.4 \times 10^6 M_\odot$ with a fixed softening length for stars of 0.7 kpc at $z=0$ and an adaptive softening for gas cells with a minimum of 0.185 comoving kpc. Throughout the text, cold gas refers to non-star forming gas with $\log(T/K) < 4.2$ (to be compared with neutral hydrogen), while hot gas refers to gas with $\log(T/K) > 6$. Additionally, ‘star-forming gas’ is used when the gas density exceeds the threshold for star formation, $n_{\text{gas}} = 0.13 \text{ cm}^{-3}$.

To identify GLSB galaxies, we use two-component (bulge+disk) surface photometry fitting (Xu et al. 2017) and create a candidate list. Through visual inspection, we identified one object (Central, hereafter), bearing a resemblance to Malin 1 in the stellar and gaseous morphologies. The SUBFIND ID of the Central at $z = 0$ is 252245. Not only is the size of the disk in this galaxy the largest in the list, it has the largest cold gas mass in the entire galaxy catalogue.

Fig. 1 shows the stellar and gas disks from edge-on and face-on views. Without the stars formed later than $z = 0.3$, the Central is just a massive elliptical galaxy with a spherical stellar halo. The recently formed stars, on the other hand, are located in an extended disk with many apparent stellar “knots”. These knots are groups of newly formed stars from gas-rich clumps in the disk without associated dark matter haloes. Most of the stars in the disk are formed within the last 1.5 Gyr ($\zeta_{\text{form}} = 0.1$, blue dots in Fig. 1). Also, there is not any clear stellar age gradient across the disk. Many of the features including the stellar “knots”, young stellar population, spiral structure, and lack of age gradient agree well with the observations of Malin 1 (Boissier et al. 2016).

The gas distribution is in an extended and well-organized disk with a radius larger than 100 kpc. In the right panels of Fig. 1, we show the cold gas in gray and star-forming gas in red. An exponential profile well describes the projected surface density profile of the gas disk, with a scale length of 37 kpc. Moreover, the surface density of the cold gas is one order of magnitude larger than the surface density of stars, highlighting the galaxy’s gas-rich nature.

Figure 2 shows the circular velocity curves from the total mass distribution $V_c = \sqrt{GM(r)/r}$ as well as the contribution from each component. The tangential velocity of the gas cells in the disk plane is shown with the gray scatter points. The gas disk rotates close to the circular velocity curve, and is therefore rotationally supported. Within the inner 20 kpc, the stellar mass dominates the mass budget.
to the circular velocity curve determined by the mass distribution. The gas rotation curve stays flat up to 200 kpc, which qualitatively agrees with Lelli et al. (2010). Moreover, this galaxy has a $V_{\text{max}}$ of 430 km s$^{-1}$ which is in excellent agreement with the values derived by Boissier et al. (2016).

To shed light on the formation mechanism of such an extended stellar/gas disk, we use a merger tree (Rodriguez-Gomez et al. 2015) to trace back its formation history. Interestingly, we find the disk appeared only after $z = 0.3$, when a merger event occurred. The merger event involves a pair of in-falling galaxies with peak circular velocities of 350 and 120 km s$^{-1}$ respectively. The top half of Fig. 3 shows the orbits of the two galaxies, which were orbiting around each other between $z = 1.5$ and 0.8 while inspiralling into the Central. The more massive galaxy (Intruder A) sinks more rapidly in the potential well after $z = 0.5$ due to stronger dynamical friction and completely merges with the Central at $z = 0.16$. Meanwhile, this intruder also completely disrupts the original gas disk of the Central (was visible as an edge-on disk in the center of the gas image at $z = 0.3$). Additionally, very little gas is directly delivered by Intruder A, which has lost most of its gas mass since $z = 1$ when it was still fairly distant (625 comoving kpc) from the Central.

The less massive intruder (Intruder B), on the other hand, is quite gas-rich. The interaction between the galaxies in the pair has already liberated a great deal of gas from this object to form an elongated gas trail started from $z = 0.4$. Part of the leading arm of the cold gas closely follows Intruder A. By $z = 0.3$, the leading arm has already penetrated into 100 kpc from the Central. Since then an extended rotating gas disk, as shown in the lower half of Fig. 3, forms and builds up. By $z = 0$, Intruder B has not been completely disrupted yet. To see where the cold gas came from, we also color the gas cells with temperature between $10^5$ and $10^6$ K.

Figure 4. Top panel: Total gravitationally bound gas mass as a function of redshift. While Intruder A has much gas until $z = 1$, it loses most of the gas since then. On the other hand, Intruder B has retained most of its gas mass until $z = 0$ despite having a lower $V_{\text{max}} = 120$ km s$^{-1}$. Bottom panel: The mass of neutral hydrogen within 125 kpc from the Central and the two intruders, respectively. For the Central, its neutral hydrogen mass has grown by a factor of at least three since $z = 0.2$. Among the Central and Intruder A or B, none of the three has gained this amount of neutral hydrogen prior to the merger event. The increase of neutral hydrogen within Intruder A since $z = 0.5$ is caused by its proximity to the Central because the cold gas is not gravitationally bound to Intruder A.

Figure 3. Top half: Orbits of the galaxy pair, Intruder A and B, into the Central from $z = 2$ to 0. The central red sphere has a radius of 125 kpc, the size of the final gas disk. We also label several redshifts along with galaxy trajectories to guide the readers. Lower half: The formation of a very extended gas disk from $z = 0.3$ to $z = 0$. In addition to cold gas (gray) and star-forming gas (red), we show the gas cells with temperature between $10^5$ and $10^6$ K in green. Intruder A, with a peak $V_{\text{max}} = 350$ km s$^{-1}$, sank into the central potential faster than Intruder B, with a peak $V_{\text{max}} = 120$ km s$^{-1}$. While Intruder A is gas poor, there is much cold gas associated with Intruder B. The leading gas arm of Intruder B follows the trajectory of Intruder A, seen as the one arm structure at $z = 0.3$, and triggers efficient cooling of hot halo gas, which is confirmed with the location of gas with temperature between $10^5$ and $10^6$ K.
it ionally bound gas as a function of redshift. While Intruder A was gas-rich at high $z$, it has lost most of its gas mass since $z = 1$. On the other hand, Intruder B has retained most of its gas mass until $z = 0$, despite having a lower $V_{\text{vir}}$. We further compute the mass of neutral hydrogen within 125 kpc from the three galaxies using two methods (Vogelsberger et al. 2014b; Marinacci et al. 2017a, their method 1). The results, shown in the lower panel with solid and dashed lines respectively, demonstrate that the two methods are entirely consistent. The mass of neutral hydrogen within Intruder A has gradually declined, so has its total gas mass. The increase in the amount of neutral hydrogen within Intruder A is due to its proximity to the Central, but the cold gas is gravitationally bound only to the Central. The Central has grown its neutral hydrogen mass by a factor of least three since $z = 0.2$.

At $z = 0$, the mass of cold gas within 125 kpc from the Central (the size of the final gas disk) is $1.8 \times 10^{11} M_\odot$, which is much higher than the total gas mass that can be delivered by Intruder A or B. The total mass of neutral hydrogen within the Central is significantly higher, $1.3 \times 10^{11} M_\odot$. To identify the origin of the cold gas, we use tracer particles (Genel et al. 2013) to study their thermal histories. We select tracer particles within the cold gas disk and tracer particles in the hot halo gas, both within 125 kpc from the Central.

The left panel of Fig. 5 shows the temperature histories of the cold gas in the Central identified at $z = 0$. In this plot, we show the gas temperature distribution evolution with redshift. The evolution of gas temperature shows that most of the cold gas mass came from the cooling of million-degree hot gas, which is triggered at $z \approx 0.3$. The central panel shows the distribution of cooling times for the hot gas within a radius of 250 kpc. Starting from $z \approx 0.2$, we observe a strong increase of the gas mass with a cooling time shorter than 1 Gyr. The right panel shows the density fluctuations as a function of radius for hot gas, which is a necessary condition for efficient cooling. The largest fluctuations are observed to occur at $z = 0.2$ and 0.1, when the cold gas mass sharply increased.

3 DISCUSSIONS

The fact that a similarly extended gas/stellar disk as Malin 1 has formed in a cosmological simulation is encouraging. As Boissier et al. (2016) argued, the distinct spiral structure and the lack of past bursts of star formation are difficult to explain by the ring galaxy model (Mapelli et al. 2008). A coplanar accretion of a dwarf can lead to an extended disk (Peharrubia et al. 2006). However, this process cannot reproduce the observed flat gas rotation curve out to 100 kpc (Lelli et al. 2010) if Malin 1 has a similar mass as M31 (as in Peharrubia et al. 2006). A slowly evolving disk with large angular momentum and a low level of star formation over cosmic time (Boissier et al. 2016; Impey & Bothun 1989) is also difficult to realize with our current cosmology and galaxy formation theory. Assuming our Galaxy has a typical spin, a spin parameter twenty times larger is exceptional (5σ away from the mean) although mergers can certainly help build up the spin parameter for massive halos (Zuia & Springel 2017). More importantly, the disk has yet to survive frequent mergers or flybys since high $z$ (Rodriguez-Gomez et al. 2017). Overall, it is challenging to reconcile a slowly evolving gas disk of ~ 100 kpc size within a classical inside-out formation in ΛCDM.

In contrast, the mechanism we identified in this study is able to explain the extended gas/stellar disks, the spiral structure, high gas fraction, as well as a flat rotation curve out to 200 kpc. The lack of an age gradient across the disk agrees with the recent observations by Boissier et al. (2016). The distribution of stellar ages in the extended disk (continuous star formation since $z = 0.3$) is also consistent with the range (0.1 to 3 Gyr) found by Boissier et al. (2016). The exceptional cold gas mass can be explained by the cooling of hot halo gas triggered by an external supply of cold gas, i.e. stimulated accretion. The entire picture has some similarities to the one proposed by Hagen et al. (2016). However, the galaxies in the pair are both more massive than typical dwarfs. In addition, a large mass fraction of the cold gas originated from the hot gas halo.

We find that only one galaxy contains a massive extended gas disk comparable to Malin 1 in the entire volume. Hot halo gas has been shown to be stable against cooling from tiny perturbations (Binney et al. 2009; Joung et al. 2012). On the other hand, favorable conditions for hot halo gas to cool are present with an external supply of cold gas (Keres & Hernquist 2009; Marinacci et al. 2011) or turbulence (Gaspari et al. 2017, 2018). In particular, the entropy mixing between cold gas and hot gas in the turbulent wakes is an effective channel for hot gas to cool and condense (Marinacci et al. 2011; Armillotta et al. 2016). The cooling process in this study can also be viewed as a very special case in the top-down cold gas condensation framework, which plays a crucial role in AGN feeding and star formation in early-type galaxies (for details, see Gaspari et al. 2017).

The large angular momentum of the final gas disk is a result of the orbital angular momentum in the cold gas stream. We note that the in-spiral of Intruder A has also spun up the hot gas substantially, from almost no rotation at $z = 1$, to a specific angular momentum within 250 kpc of $1.5 \times 10^3$ kpc km s$^{-1}$ at $z = 0.3$, which is ~50% of the value for cold gas. The angular momenta of cold and hot gas are also well aligned. It is possible that the rarity of Malin 1 analogues is a consequence of requiring a pair of galaxies on a specific in-spiral orbit with much cold gas in at least one member. Model refinements with higher resolution would be useful to determine the relative importance of each factor at play and reduce the numerical mixing.

Observationally, previous studies have hinted at a possible perturber close to Malin 1 (Moore & Parker 2006; Reshetnikov et al. 2010). Our study suggests yet another potential culprit in building up the massive gas disk may still be hundreds of kpc away, which could be SDDSJ123708.91+142253.2 (Galaz et al. 2015). Some neutral hydrogen bridge between SDDSJ123708.91+142253.2 and Malin 1 will be a strong evidence for the scenario we discussed here. Also, the presence of an extended old stellar halo around Malin 1 can be revealed, in principle, with deep photometry to confirm it as a massive galaxy. Due to the large distance of Malin 1, these observational tests are non-trivial. Fortunately, there are similar nearby galaxies such as UGC 1382 (Hagen et al. 2016) which offer a more feasible alternative. Another important test is to establish whether the kinematics and metallicity pattern of the outer extended stellar/gas disk are distinct from the central regions, as expected from our scenario.

4 CONCLUSIONS

We have found a Malin 1 analogue in the 100 Mpc IllustrisTNG volume. This galaxy reproduces well the observed features of Malin 1’s vast disk. The exceptional disk size is a result of hot gas cooling triggered by an ample supply of cold gas due to a pair of in-falling galaxies. This formation mechanism could reconcile the peculiarities of Malin 1’s extended stellar disk within current galaxy formation theory in ΛCDM.

Finally, we note that the conditions that led to the formation of the simulated galaxy are similar to the present state of the Milky
Figure 5. Left panel: Gas temperature history of the cold gas identified at \( z = 0 \) for the Central using tracer particles. We show the 10th, 20th up to 90th percentiles at each redshift. The median value of gas temperature (solid thick line) indicates more than half of the cold gas originated from million-degree hot gas at \( z = 0.3 \). Middle panel: The distribution of cooling times for the hot halo gas within 250 kpc from the Central at each redshift. We observe a strong increase of gas mass with cooling time scale shorter than 1 Gyr between \( z \sim 0.2 \) and 0. Right panel: The density fluctuations \( \delta \rho/\rho \) of hot gas, a necessary condition for efficient gas cooling, as a function of radius at different epochs.

Way. Our Galaxy is interacting with a pair of galaxies, the Magellanic Clouds, and an extended gas structure, the Magellanic Stream. Theories suggest that the Clouds are on their first passage through the Milky Way (Besla et al. 2007) and that the Stream resulted from the interaction between the Clouds (Besla et al. 2010). Based on these similarities to the object in IllustrisTNG, we speculate that the Milky Way may develop an extended disk of its own in the future through the stimulated accretion of gas from its hot halo.

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