

The effects of a hot gaseous halo on disc thickening in galaxy minor mergers

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ABSTRACT

We employ hydrodynamical simulations to study the effects of dissipational gas physics on the vertical heating and thickening of disc galaxies during minor mergers. For the first time we present a suite of simulations that includes a diffuse, rotating, cooling, hot gaseous halo, as predicted by cosmological hydrodynamical simulations as well as models of galaxy formation. We study the effect of this new gaseous component on the vertical structure of a Milky Way-like stellar disc during 1:10 and 1:5 mergers. For 1:10 mergers we find no increased final thin disc scale height compared to the isolated simulation, leading to the conclusion that thin discs can be present even after a 1:10 merger if a reasonable amount of hot gas is present. The reason for this is the accretion of new cold gas, leading to the formation of a massive new thin stellar disc that dominates the surface brightness profile. In a previous study, in which we included only cold gas in the disk, we showed that the presence of cold gas decreased the thickening by a minor merger relative to the no-gas case. Here, we show that the evolution of the scale height in the presences of a cooling hot halo is dominated by the formation of the new stellar disc. In this scenario, the thick disc is the old stellar disc that has been thickened in a minor merger at $z \gtrsim 1$, while the thin disc is the new stellar disc that reforms after this merger. When galactic winds are also considered, the final scale height is larger due to two effects. First, the winds reduce the star-formation rate leading to a less massive new stellar disc, such that the thickened old disc still dominates. Second, the winds exert a pressure force on the gas in the disc, leading to a shallower gas profile and thus to a thicker new stellar disc. In addition, we study the evolution of the scale height during a 1:5 merger and find that a thin disc can be present even after this merger, provided enough hot gas is available. The final scale height in our simulations depends on the mass of the hot gaseous halo, the efficiency of the winds and the merger mass ratio. We find post-merger values in the range $0.5 \lesssim z_0 \lesssim 1.0$ kpc in good agreement with observational constraints by local galaxies.

Key words: Galaxy: disc, evolution, structure – galaxies: evolution, interactions – methods: numerical

1 INTRODUCTION

In the current paradigm of structure formation, large objects, such as galaxies or clusters, are believed to form hier-

archically, through a ‘bottom-up’ (White & Rees 1978) process of merging. In modern galaxy formation theories, this merging process drives the evolution of many galaxy properties. While major (near-equal mass) mergers can fully transform disc-dominated systems into elliptical galaxies (Toomre 1977; Negroponte & White 1983; Hernquist 1992; Naab &

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Burkert 2003; Cox et al. 2006), minor (unequal mass) mergers are believed to merely thicken the galactic disc (Quinn et al. 1993; Brook et al. 2004; Bournaud et al. 2005; Read et al. 2008; Qu et al. 2011).

About a decade ago, N-body simulations attained sufficient dynamic range to reveal that, in Cold Dark Matter (CDM) models, all haloes should contain a large number of embedded subhaloes that survive the collapse and virialization of the parent structure (Klypin et al. 1999; Moore et al. 1999). Studies on merger statistics find that roughly half of the mass delivery through mergers into a dark matter halo of mass M_h is due to systems with masses $M_{\text{sat}} = (0.03 - 0.3)M_h$. A large fraction (95 per cent) of Milky Way (MW) sized haloes have accreted a satellite with a virial mass comparable with the total mass of the MW disc ($\sim 0.03M_h$). About 70 per cent of the haloes experienced a 1:10 merger since $z \sim 1$, while ~ 40 per cent had a 1:5 merger (Stewart et al. 2008; Fakhouri et al. 2010; Genel et al. 2010).

This large population of merging satellites has raised the question of whether mergers are *too* common in the Λ CDM scenario. Numerous studies have questioned whether thin, dynamically fragile discs such as the one observed in the MW can survive this bombardment by incoming satellites and found that the answer depends quite sensitively on the mass ratio of the merging galaxies (e.g. Quinn & Goodman 1986; Toth & Ostriker 1992; Quinn et al. 1993; Walker et al. 1996; Huang & Carlberg 1997; Velazquez & White 1999; Font et al. 2001; Benson et al. 2004; Gauthier et al. 2006; Kazantzidis et al. 2008, 2009; Villalobos & Helmi 2008; Purcell et al. 2009). There seems to be a consensus that the main danger to thin discs is from events with a dark matter mass ratio of ($\sim 1:10$). The ubiquitous mergers with a lower mass satellite of $M_{\text{sat}} \lesssim M_{\text{disc}}$ do not destroy the thin disc (Kazantzidis et al. 2008). On the other hand, mergers with a very massive satellite are rare such that only few disc systems are affected. However, mergers with an intermediate mass ratio of 1:10 are frequent enough for MW-sized systems, and in dissipationless simulations these events destroy the thin stellar disc. This would imply that thin discs in MW-sized systems are rare, in disagreement with the observation of many systems with thin discs in the Universe (e.g. Schwarzkopf & Dettmar 2000; Yoachim & Dalcanton 2006).

Previous studies of disc stability against satellite infall have often been affected by numerical limitations or by analytic assumptions that have later been found to be contradicting the Λ CDM model. Typical problems include initial discs that are rather thick compared to observations of local disc galaxies (Quinn et al. 1993; Velazquez & White 1999; Font et al. 2001; Villalobos & Helmi 2008), the modelling of structural components as rigid potentials (Quinn & Goodman 1986; Quinn et al. 1993; Huang & Carlberg 1997), the negligence of the dark matter component of the satellite (Quinn et al. 1993; Walker et al. 1996; Velazquez & White 1999), and the use of satellite orbital parameters that are in conflict with the standard cosmology. Also in analytic models, simplifications had to be assumed, such as the local deposition of the orbital energy of the satellite (Toth & Ostriker 1992), and the absence of global heating modes (Benson et al. 2004). More importantly, most studies so far, have neglected the gaseous component in the galaxy.

However, the presence of a dissipative gas component is now known to play an important role in galaxy mergers and is crucial in order to reproduce basic properties of observed galaxies (Mihos & Hernquist 1994; Naab et al. 2006). Unlike stars and dark matter, gas is able to cool radiatively, thereby losing kinetic energy efficiently. Furthermore, as the gas is eventually transformed into stars, a new rotating, kinematically cold stellar disc can form during and after a merger. Therefore, a dissipative component in the galactic disc has a stabilising effect. Moster et al. (2010b, M10) found that when the presence of gas in the disc is taken into account, the thickening of the stellar disc is reduced. For an initial disc gas fraction of 20 (40) per cent, the thickening was reduced by 25 (50) per cent with respect to collisionless simulations. Final disc scale heights found in the simulations are in good agreement with studies of the vertical structure of spiral galaxies.

In M10, we argued that the presence of gas can reduce disc heating via two mechanisms: absorption of kinetic impact energy by the gas and/or formation of a new thin stellar disc that can cause heated stars to recontract towards the disc plane. As in the initial conditions only the cold gas in the disc was accounted for (neglecting the gaseous halo), most of the gas was consumed during the merger, and therefore the regrowth of a new thin disc had a negligible impact on the scale height of the post-merger galaxy. This led to the conclusion that the main process that suppresses disc thickening in the absence of a continuous supply of fresh gas is the absorption of impact energy by the gas. Furthermore, M10 concluded that in order to reform a new thin disc comparable in mass to the old disc, an external fueling reservoir, such as cooling and accretion from a gaseous halo, is needed.

While M10 focused their attention only on the cold gas component within the disc, semi-analytic models of galaxy formation (Kauffmann et al. 1993; Bower et al. 2006; Somerville et al. 2008) as well as full cosmological hydrodynamic simulations (e.g. Toft et al. 2002; Sommer-Larsen 2006; Johansson et al. 2009; Rasmussen et al. 2009; Stinson et al. 2010; Hansen et al. 2010) both predict a large amount of hot gas in quasi-hydrostatic equilibrium within the gravitational potential of the dark matter halo. Cooling and accretion of gas from these haloes can grow the discs of spiral galaxies (e.g. Abadi et al. 2003; Sommer-Larsen et al. 2003). It is therefore expected that the presence of a hot gaseous halo leads to the growth of a new thin stellar disc that may affect the evolution of the disc scale height.

In this paper we expand our previous work on disk stability by studying the effects of gas cooling from a hot reservoir on the vertical structure of the disc in a MW-like galaxy during minor mergers. We extend our previous study by re-simulating the fiducial initial conditions from M10 (1:10 (dark matter mass ratio) merger with 20 per cent of cold gas in the disc, an orbital inclination of 60° and an initial disc scale height of $z_0 = 0.4$ kpc), now including a hot gaseous halo. We assume that the mass of hot gas in the halo is such that the whole system contains 85 percent of the universal baryon fraction. We also run the same system in isolation, in order to study how the accretion of gas from the halo acts on the scale height.

We then present a detailed analysis of the effects of this new gas component. We focus our attention on the trans-

formation of the initial stellar disc into a thick disc and the regrowth of a new thin stellar disc after the mergers. The continuous accretion of gas and the reformation of a massive thin disc is expected to affect the evolution of the disc scale height. On the one hand the potential of the new disc can cause heated stars to recontract towards the disc plane; on the other hand the new thin disc can dominate the surface brightness and therefore lead to a lower observed scale height.

We further study the effects of galactic winds on the evolution of the scale height. As winds reduce the SFR, the new stellar disc is expected to be less massive such that the surface brightness profile is dominated by the thickened old disc. In addition, winds can exert a pressure force on the gas in the disc, leading to a thicker gas disc and thus to a thicker new disc than in the windless case. We demonstrate how these two effects impact the evolution of the scale height in our simulations.

Finally, we investigate how the same galactic disc evolves in a 1:5 merger (dark matter mass ratio). As the effects from the hot gaseous halo are expected to further decrease the final scale height, we study whether the disc can survive such a merger if the hot component is included and whether the final scale height is in agreement with observational constraints.

The paper is organised as follows: in section 2 we provide a brief summary of the GADGET-2 code and the initial conditions. We also summarise how the initial conditions have been expanded in order to include a rotating hot gaseous halo. In section 3 we present our results for the 1:10 merger simulations, focusing on the differences between the simulations with and without a hot gaseous component and on the effects of the galactic winds. In section 4 we show the results for the 1:5 minor merger simulations and study how the disc thickening is changed when a hot halo is included. Finally, in section 5 we summarise and discuss our results and compare them to previous studies that have neglected the gaseous halo.

2 NUMERICAL SIMULATIONS

2.1 Numerical Code

We employ the parallel TreeSPH-code GADGET-2 (Springel 2005) to conduct the numerical simulations presented in this paper. The gaseous component is evolved using the Lagrangian Smoothed Particle Hydrodynamics (SPH Lucy 1977; Gingold & Monaghan 1977; Monaghan 1992) technique, employed in a formulation that conserves both energy and entropy (Springel & Hernquist 2002). Radiative cooling is implemented for a primordial mixture of hydrogen and helium following Katz et al. (1996), including a spatially uniform time-independent local photo-ionizing UV background in the optically thin limit (Haardt & Madau 1996).

The implementation of star formation and the associated heating by supernovae (SN) follows the sub-resolution multiphase ISM model developed by Springel & Hernquist (2003). This model assumes that a thermal instability operates above a critical density threshold ρ_{th} , such that the ISM is a two-phase medium with cold clouds embedded in a tenuous gas at pressure equilibrium. Stars form in dense

regions on a timescale chosen to match observations (Kennicutt 1998) and short-lived stars supply energy to the surrounding gas as supernovae heating the diffuse phase.

The threshold density ρ_{th} is determined self-consistently by demanding that the equation of state (EOS) is continuous at the onset of star formation. SN-driven galactic winds as proposed by Springel & Hernquist (2003) are included in a subset of simulations. In this model the mass-loss rate carried by the wind is proportional to the star formation rate (SFR) $\dot{M}_w = \eta \dot{M}_*$, where the wind efficiency is quantified by the mass-loading-factor η . The wind is assumed to carry a fixed fraction of the supernova energy, leading to a constant initial wind speed v_w .

We adopt the standard parameters for the multiphase model in order to match the Kennicutt Law as specified in Springel & Hernquist (2003). The star formation timescale is set to $t_*^0 = 2.1$ Gyr, the cloud evaporation parameter to $A_0 = 1000$ and the SN “temperature” to $T_{SN} = 10^8$ K. A Salpeter (1955) initial mass function (IMF) is assumed, setting the mass fraction of massive stars to $\beta = 0.1$. We further adopt a mass-loading factor of $\eta = 2$ and a wind speed of $v_w \sim 480 \text{ km s}^{-1}$, typical for a MW-like galaxy at low redshift. We do not include feedback from accreting black holes (AGN feedback) in our simulations.

2.2 Galaxy Models

The galaxy models used in our simulations are constructed with the method developed by Springel et al. (2005) with the extension to include a hot gas halo as described by Moster et al. (2011, M11). Each primary system (i.e. the central galaxy) is composed of a cold gaseous disc, a stellar disc and a stellar bulge with masses M_{cg} , M_{disc} and M_b embedded in a halo that consists of hot gas and dark matter with masses M_{hg} and M_{dm} . The satellite systems only consist of dark matter and a spherical stellar component.

The dark matter halo has a Hernquist (1990) profile with a scale radius a corresponding to a Navarro-Frenk-White (NFW; Navarro et al. 1997) halo with a scale length r_s and a concentration parameter $c = r_{vir}/r_s$. The gaseous and stellar discs are rotationally supported and have exponential surface density profiles with an equal scale length r_d . The vertical structure of the stellar disc is described by a radially independent sech^2 profile with a scale height z_0 , such that the stellar density is described by

$$\rho_*(R, z) = \frac{M_{disc}}{4\pi z_0 r_d^2} \text{sech}^2\left(\frac{z}{z_0}\right) \exp\left(-\frac{R}{r_d}\right). \quad (1)$$

The vertical velocity dispersion is set equal to the radial velocity dispersion. The gas temperature is fixed by the EOS, rather than the velocity dispersion. The vertical structure of the gaseous disc is computed self-consistently as a function of the surface density by requiring a balance of the galactic potential and the pressure given by the EOS. The spherical stellar bulge is non-rotating and has a Hernquist (1990) profile with a scale length r_b .

We model the hot gaseous component as a slowly rotating halo with a spherical density profile (Moster et al. 2011). The density distribution follows the observationally motivated β -profile (Cavaliere & Fusco-Femiano 1976; Jones & Forman 1984; Eke et al. 1998):

Table 1. Parameters kept constant for all simulations. Masses are in units of $10^{10}M_{\odot}$, scale and softening lengths are in units of kpc and pc, respectively

System	M_{dm}	M_{disc}	M_{b}	r_{d}	r_{g}	r_{b}	z_0	c	N_{dm}	N_{disc}	N_{bulge}
Primary	100	2.4	0.600	3.00	3.0	0.50	0.4	9.65	2 000 000	500 000	250 000
Sat (1:10)	20	0.0	0.063	0.00	0.0	0.30	0.0	11.98	450 000	0	50 000
Sat (1:5)	10	0.0	0.162	0.00	0.0	0.35	0.0	11.45	900 000	0	130 000

$$\rho_{\text{hg}}(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2}\beta}. \quad (2)$$

which has three free parameters: the central density ρ_0 , the core radius r_c and the outer slope parameter β .

The temperature profile is fixed by assuming an isotropic model and hydrostatic equilibrium inside the galactic potential. Furthermore, the hot gaseous halo is rotating around the spin axis of the disc with a specific angular momentum j_{hg} that is a multiple of the specific angular momentum of the dark matter halo j_{dm} such that $j_{\text{hg}} = \alpha j_{\text{dm}}$. The angular momentum distribution scales with the product of the distance from the spin axis R and the circular velocity at this distance: $j(R) \propto R v_{\text{circ}}(R)$.

2.3 Simulation Parameters

We select the same parameters for the fiducial galaxy models as M10. For the primary disc galaxy system we use a virial mass of $M_{\text{dm}} = 10^{12}M_{\odot}$ and a concentration parameter of $c = 9.65$, following Macciò et al. (2008). The stellar mass of the galaxy is determined using the empirical relation derived by Moster et al. (2010a), which yields $M_{*,\text{pri}} = 3 \times 10^{10}M_{\odot}$, resulting in a stellar-to-halo mass ratio of 1:33. Distributing 80 per cent of this stellar mass into the disc results in a stellar disc mass of $M_{\text{disc}} = 2.4 \times 10^{10}M_{\odot}$ and a bulge mass of $M_{\text{bulge}} = 0.6 \times 10^{10}M_{\odot}$.

For models with a cold gaseous disc we add $M_{\text{cg}} = 0.6 \times 10^{10}M_{\odot}$ such that the gas fraction in the disc is 20 per cent. We set the scale lengths of the stellar and the gaseous disc to $r_{\text{d}} = 3$ kpc, which fixes the spin parameter to $\lambda = 0.033$ for the case without gas and $\lambda = 0.034$ for the models with cold gas in the disc. We set the scale height of the stellar disc to $z_0 = 0.4$ kpc and the bulge radius to $r_{\text{b}} = 0.5$ kpc.

In addition to the models employed in M10 we create a system that also includes a hot gaseous halo. We fix the mass of this halo by assuming that the baryonic fraction within the virial radius of the system is 85 per cent of the Universal one. This leads to a hot gas halo mass of $M_{\text{hg}} = 1.1 \times 10^{11}M_{\odot}$ within r_{vir} . For the density profile, we adopt $\beta = 2/3$ (Jones & Forman 1984) and $r_c = 0.22r_s$ (Makino et al. 1998). The spin parameter α has been constrained by Moster et al. (2011) using isolated simulations of a MW-like galaxy and demanding that the observed evolution of the average stellar mass and scalelength be reproduced. M11 found the best agreement with the observational constraints with a spin factor of $\alpha = 4$ which will also be assumed throughout this work. In this way our disc galaxy models have a consistent evolution since $z = 1$.

The satellite systems consist of only dark matter and a

stellar bulge. We employ two (dark matter) mass ratios for the merger, 1:10 and 1:5. For the 1:10 merger the dark matter mass of the satellite is $M_{\text{dm}} = 10^{11}M_{\odot}$ with a concentration of $c = 11.98$. The dark matter mass of the satellite for the 1:5 merger is $M_{\text{dm}} = 2 \times 10^{11}M_{\odot}$ with a concentration of $c = 11.45$. Using the stellar-to-halo mass relation we derive a stellar mass of $M_{\text{b}} = 6.3 \times 10^8M_{\odot}$ for the 1:10 merger and a stellar mass of $M_{\text{b}} = 1.62 \times 10^9M_{\odot}$ for the 1:5 merger. The stellar-to-halo mass ratio of the satellites is 1:159 and 1:62 for the 1:10 and 1:5 mergers, respectively. Finally we fix the bulge scale lengths at $r_{\text{b}} = 0.3$ kpc and $r_{\text{b}} = 0.35$ kpc for the 1:10 and 1:5 mergers, respectively.

The primary system is modelled with $N_{\text{dm}} = 2 \times 10^6$ dark matter, $N_{\text{disc}} = 5 \times 10^5$ stellar disc, $N_{\text{cg}} = 3.1 \times 10^4$ gaseous disc, $N_{\text{bulge}} = 2.5 \times 10^5$ bulge and $N_{\text{hg}} = 6.5 \times 10^5$ gaseous halo particles. The satellite system has $N_{\text{dm}} = 4.5 \times 10^5$ ($N_{\text{dm}} = 9 \times 10^5$) dark matter and $N_{\text{bulge}} = 5 \times 10^4$ ($N_{\text{bulge}} = 1.3 \times 10^5$) bulge particles for the 1:10 (1:5) merger.¹

We set the gravitational softening length to $\epsilon = 70$ pc, 100 pc and 140 pc for stellar, gas and dark matter particles, respectively. The merger orbit has been chosen to be consistent with cosmological simulations and has an eccentricity of $\epsilon = 0.89$, a pericentric distance of $r_{\text{min}} = 18$ kpc and an initial separation of $d_{\text{start}} = 120$ kpc. We use a prograde orbit with an angle of $\theta = 60^\circ$ between the spin axes of the disc and the orbit and evolve the simulations for 6 Gyr. Prograde orbits are expected to be more destructive to the disc than retrograde mergers (Velazquez & White 1999).

We summarise the parameters that are kept constant for all simulations in Table 1, and specify all parameters that differ for the various simulation runs in Table 2. The different simulations are labeled with the first letter I for isolated runs and an M for mergers. The second letter specifies the gas fraction of the disc (A for $f_{\text{gas}} = 0$ and B for $f_{\text{gas}} = 0.2$) followed by a number that indicates the merger mass ratio. If a hot gaseous halo included an ‘h’ is added and if galactic winds are included we add a ‘w’.

3 RESULTS FOR THE 1:10 MERGER

In order to study the evolution of the disc thickness, we compute the edge-on projected surface density as a function of the distance to the galactic plane at a distance of

¹ This choice of particle numbers results in a resolution that is a factor of two lower in dark matter and initial stars and a factor of four lower in gas and newly formed stars than that employed by M10. The impact of this lowered resolution on our results is discussed in section 3.4.

Table 2. Parameters for the different simulation runs. Masses are in units of $10^{10}M_{\odot}$, and softening lengths are in units of pc.

Run	f_{gas}	M_{cg}	M_{hg}	N_{cg}	N_{hg}	λ	η	v_{wind}	θ	ratio
IA	0.0	0.0	0.0	0	0	0.033	0.0	0	-	-
IB	0.2	0.6	0.0	31 250	0	0.034	0.0	0	-	-
IBh	0.2	0.6	11.5	31 250	650 000	0.034	0.0	0	-	-
IBw	0.2	0.6	0.0	31 250	0	0.034	1.0	480	-	-
IBhw	0.2	0.6	11.5	31 250	650 000	0.034	1.0	480	-	-
MA10	0.0	0.0	0.0	0	0	0.033	0.0	0	60°	1:10
MB10	0.2	0.6	0.0	31 250	0	0.034	0.0	0	60°	1:10
MB10h	0.2	0.6	11.5	31 250	650 000	0.034	0.0	0	60°	1:10
MB10w	0.2	0.6	0.0	31 250	0	0.034	1.0	480	60°	1:10
MB10hw	0.2	0.6	11.5	31 250	650 000	0.034	1.0	480	60°	1:10
MA5	0.0	0.0	0.0	0	0	0.033	0.0	0	60°	1:5
MB5	0.2	0.6	0.0	31 250	0	0.034	0.0	0	60°	1:5
MB5h	0.2	0.6	11.5	31 250	650 000	0.034	0.0	0	60°	1:5
MB5w	0.2	0.6	0.0	31 250	0	0.034	1.0	480	60°	1:5
MB5hw	0.2	0.6	11.5	31 250	650 000	0.034	1.0	480	60°	1:5

$R_{\odot} \sim 8$ kpc from the disc spin axis. We determine the disc scale height z_0 by fitting a sech^2 function to the edge-on surface density profile $\Sigma(z)$ at R_{\odot} to be able to compare the results to observations. We note that values for z_0 are potentially larger than what one would obtain by fitting to the 3d density profile, as the disc can develop considerable flaring (i.e. the disc becomes thicker with increasing distance from the spin axis).

3.1 Evolution of the scale height and effects of cold gas

Before studying the effects of mergers, it is important to first address the stability of the initial disc model in isolation. This allows us to disentangle instabilities of the isolated disc (both physical and numerical) from the thickening that is caused by mergers. The evolution of the disc scale height for the isolated galaxy and 1:10 merger simulations for the case without galactic winds is shown in Figure 1.

The result for the simulation of the isolated galaxy without gas (IA) is given by the red dotted line. The scale height increases from an initial value of $z_0 = 0.4$ kpc to a final value of $z_0 = 0.5$ kpc, which means that the instabilities of the isolated disc lead to an increase of 25 per cent. This effect is mainly numerical and will be further discussed in section 3.4. On the other hand, any further increase of the scale height should be due to accretion events. If cold gas is included in the disc, the final scale height is slightly lower, due to the new thin stellar disc that forms from the cold gaseous disc through star formation. Although this new disc is thinner than the old disc, its mass is much lower, such that the total scale height is very close to the result obtained for the dissipationless case.

For the 1:10 merger simulations we find that the disc is considerably thickened beyond the degree found for the isolated runs. The scale height for the merger without gas has a final value of $z_0 = 0.8$ kpc which implies a thickening by a factor of 2 (red solid line in Figure 1. In the simulation that includes an initial 20 per cent cold gas in the

disc (blue solid line) this thickening is reduced, resulting in a final scale height of $z_0 = 0.7$ kpc. It has been shown by M10 that the physical process that is causing this change in behaviour is the absorption of kinetic impact energy of the satellite by the gas component. The gas can efficiently radiate this energy away by cooling. On the other hand, the reformation of a new thin disc has little effect on the evolution of the scale height, as the final mass of this new stellar disc ($M_{*,\text{new}} \sim 0.5 \times 10^{10} M_{\odot}$) is much lower than the initial old disc ($M_{*,\text{old}} \sim 2.4 \times 10^{10} M_{\odot}$). As a result, the disc is thickened during the first two encounters, while afterwards, the scale height is roughly constant.

We note that the evolution of the scale height for the 1:10 merger simulations is in very good agreement with the results presented by M10, although the spatial resolution of the simulations analyzed here is lower by a factor of two. See section 3.4 for a discussion.

3.2 Effects of the hot gaseous halo

All previous studies on disc heating and thickening have either completely neglected the dissipational component, or have only included the cold gas in the disc. However, M10 concluded that the reformation of a new thin stellar disc could reduce the total scale height, if an external fuelling reservoir were available that could provide enough material such that the new disc could obtain a mass that is comparable to the old one. In this section, we study how the scale height of the disc evolves if this reservoir is provided by a rotating, cooling hot gaseous halo, as modelled by M11.

The resulting time evolution of z_0 for the isolated run including a hot gaseous component (IBh) is presented in Figure 1 (green dotted line). Although we have seen before that the initial stellar disc does thicken in an isolated run, the scale height of the total stellar disc is constant at $z_0 = 0.4$ kpc. The reason for this is the formation of a new very thin stellar disc which has a mass that is even larger than the old disc. As a result, this new disc dominates the surface density profile and compensates for the numerical

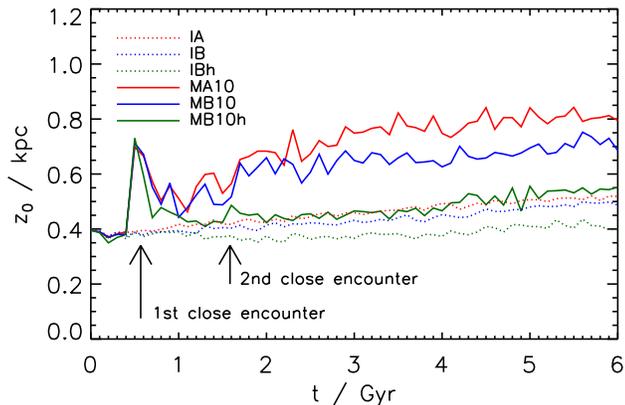


Figure 1. Evolution of the disc scale height for isolated and 1:10 merger simulations with and without a gaseous halo for the case without galactic winds.

thickening of the old disc. The scale height of the disc in the IBh simulation is thus mostly determined by how the gas accretes from the halo, i.e. on the profile of the cold gas disc.

In the 1:10 merger simulation including a hot gaseous halo (MBh, green solid line), we find a completely different behaviour than in the run without a hot component. While the scale height increases during the first and second encounters, it decreases again after the encounters. At the end of the simulation, the scale height of all stars is equal to that in the isolated run that does not include gas at all (and where all thickening is due to numerical effects) with a final value of $z_0 = 0.5$ kpc. This means that due to the gas accretion from the hot halo and the resulting new thin stellar disc the overall scale height shows no additional thickening due to the 1:10 merger with respect to the isolated dissipationless simulation. However, the scale height is still larger than in the isolated run including a hot gaseous halo.

There are two possible effects that can cause this: one option is that the potential of the new stellar disc forces heated stars to contract again onto the disc plane; the other possibility is that the new disc is both thin and massive, such that the contribution to the density profile of the total disc is large. In order to investigate this further, we compute the scale height at the end of the simulations for old stars (i.e. stars which have been set up as initial conditions) and new stars (i.e. stars that formed during the simulation). We present the resulting surface brightness profiles for old, new, and all stars in Figure 2, where we have assumed a mass-to-light ratio of $M/L = 3(M/L)_\odot$, appropriate for the MW in the B band (Zibetti et al. 2009). We find a value for the scale height of the new thin disc in MBh of $z_{0,new} = 0.45$ kpc while the old stellar disc has $z_{0,old} = 0.8$ kpc. Thus the reformation of a new massive disc has not caused the old stars to contract onto the disc plane. In the MB run, the scale height of the new disc is $z_{0,new} = 0.4$ kpc and that of the old disc is $z_{0,old} = 0.75$ kpc. Thus, although for MBh both the new and the old discs are thicker than the respective ones of MB, the total scale height is smaller. This can only be explained by the differences in mass of the new disc between MB and MBh.

To demonstrate this, we plot the SFR, the total mass of new stars formed during the simulation and the cold gas

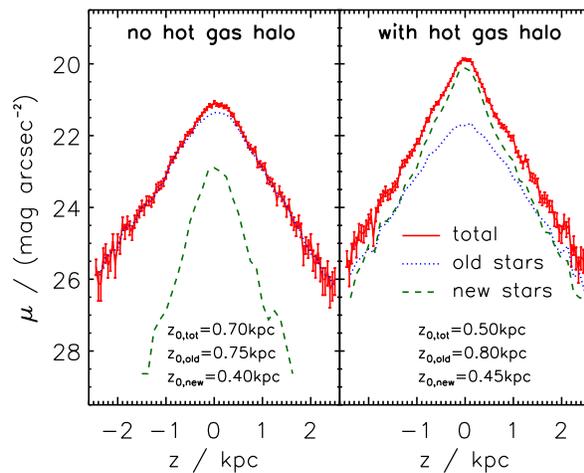


Figure 2. Final edge-on surface brightness profiles for the 1:10 merger simulations without winds at a projected radius of 8 kpc for old, new, and all stars. The left panel shows the run without a hot gaseous halo and the right panel gives the results for the run including the hot component (right panel). A mass-to-light ratio of $M/L = 3(M/L)_\odot$ has been assumed, appropriate for the Milky Way in the B band.

mass in Figure 3 (left panels). While the SFR after the second close encounter is already very low for the MB simulation ($< 1M_\odot \text{ yr}^{-1}$), the MBh run maintains a high SFR throughout the simulation ($\sim 5 - 10M_\odot \text{ yr}^{-1}$ for a Salpeter IMF). These SFRs lead to a final stellar mass (after 6 Gyr) that is roughly twice the initial value, consistent with results for low redshift galaxies from subhalo abundance matching (Moster et al. 2010a) and semi-analytic models of galaxy formation (Somerville et al. 2008). As a result of this the mass of the new thin disc is much higher in the MBh run and even exceeds that of the old stellar disc component at the end of the simulation. As the new thin disc is more massive than the old disc, the contribution to the total density profile and thus to the total scale height is dominated by the new stellar disc. As a result the scale height of the total disc in MBh is smaller than that of MB, although both the new and the old discs are thicker than those found in MB. This can also be seen in Figure 2: although the new stars in MBh form a thicker disc than in MB, they dominate the total surface brightness profile, such that it is thinner than the total profile of MB.

Another effect we notice is the formation of a more massive cold gaseous disc than the one that we started with. The mass of the cold gaseous disc quickly rises from $M_{cg} = 0.6 \times 10^{10} M_\odot$ to $M_{cg} \sim 10^{10} M_\odot$ and only decreases slightly through the course of the simulation. This means that the disc gas fraction during the first two encounters of this simulation is ~ 20 percent (while the simulation without a hot gaseous halo has only ~ 10 percent gas in the disc during the first two encounters, due to gas consumption by star formation). As the gas fraction in MBh is roughly twice the value of the MB run, the cold gas component is able to absorb more of the kinetic impact energy of the satellite. Therefore this process is also more efficient in the MBh run than in the MB run. However, as this gas fraction is comparable to the 40 per cent gas run of M10, it is not possible to explain the final scale height by this effect alone, as M10

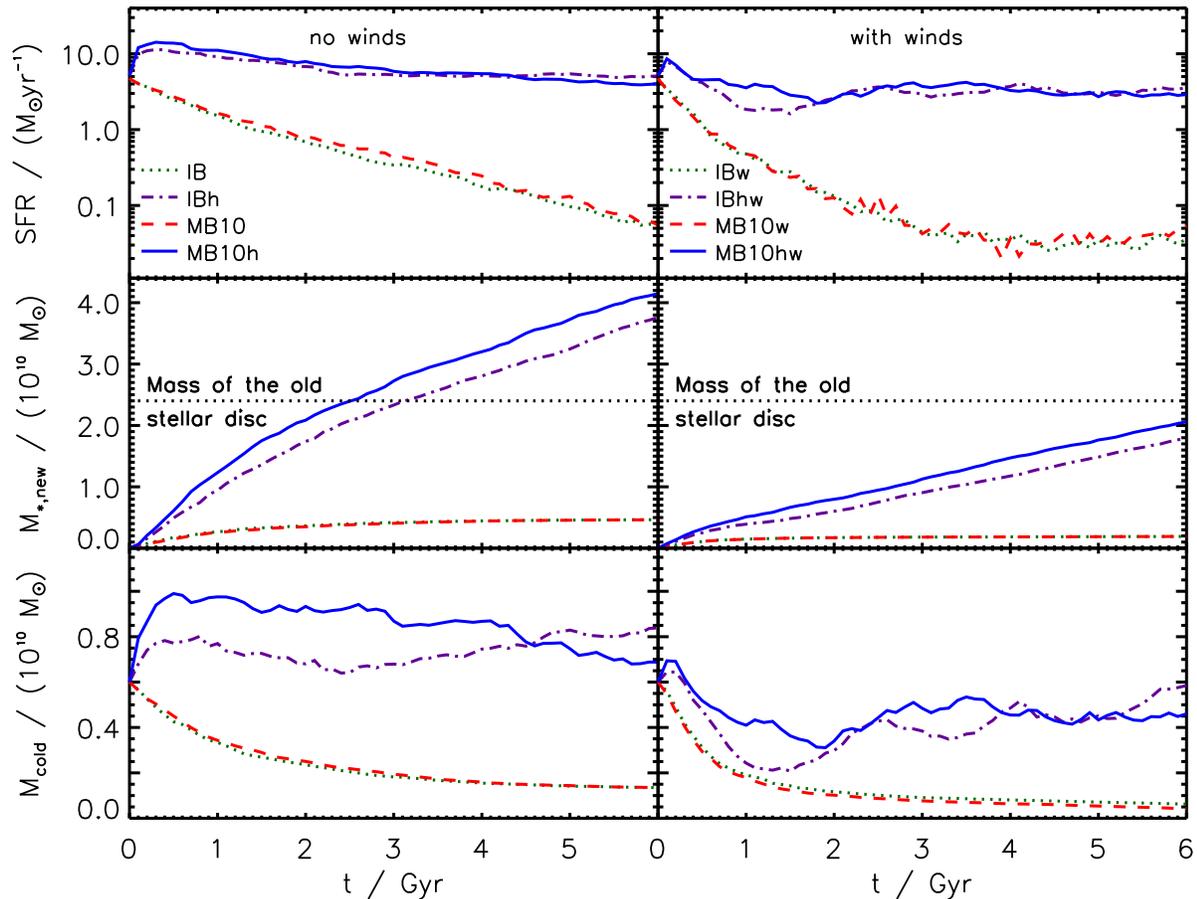


Figure 3. The rows from top to bottom show the SFR, the total mass of new stars formed during the simulation and the cold gas mass for the simulations with and without a gaseous halo. The panels on the left hand side give the results for the simulations without galactic winds, while the simulations with winds are presented on the right hand side.

showed that even an initial value of 40 percent cold gas leads to a final scale height of $z_0 = 0.6$ kpc, and thus to considerable thickening with respect to an isolated simulation. We note that the mass of the cold gas and the SFR depend on the angular momentum of the hot gaseous halo.

We thus find that the scale height of a MW-like galaxy can decrease again after having been increased by a 1:10 merger, if cooling and accretion from a gaseous halo are considered. With respect to collisionless simulations ($z_0 = 0.8$ kpc), the presence of 20 percent cold gas in the initial disc reduces the thickening by ~ 25 percent ($z_0 = 0.7$ kpc), while the accretion of gas from the hot halo further reduces the thickening. This final scale height is similar to that of an isolated dissipationless simulation, such that the 1:10 merger does not lead to a thicker disc in the end. Because accretion of new gas is expected to be ubiquitous in a cosmological context, we conclude that in order to retain thin discs, like those observed in the universe, it is not necessary to have very high initial gas fractions. Thus, a MW-like galaxy can experience a 1:10 merger without an overall increase of its scale height.

Although the new disc is very thin, the initial disc is thickened by a considerable amount, possibly explaining the origin of thick discs such as the one seen in our Galaxy. In the scenario presented here, the thick disc is the old stellar

disc that has been thickened in a minor merger at $z \gtrsim 1$, while the thin disc is the new stellar disc that reforms after this merger. In the MBh simulation the mean stellar ages of the thin and thick discs are ~ 3.5 Gyr and $\gtrsim 6$ Gyr, respectively. For the solar neighborhood the long-lived stars in the thin disc are slightly older with a mean age of ~ 4 Gyr. These results are in good agreement with the observations by Bensby et al. (2003) who analyze a sample of stars in the solar neighborhood and find mean stellar ages of 4.9 ± 2.0 Gyr and 11.2 ± 4.3 Gyr for the thin and thick disc, respectively. Using the same sample but a different method of analyzing the data (i.e. different isochrones), Feltzing et al. (2003) find mean stellar ages of 6.1 ± 2.0 Gyr and 12.1 ± 3.8 Gyr for the two discs, in agreement with our simulation. We note that the mean stellar age of the new thin disc in our model, depends on the exact redshift of the minor merger. If the satellite galaxy enters the main halo earlier than assumed in our simulation ($t_{\text{merge}} > 6$ Gyr) the mean stellar age of the new thin disc is larger, so the thin disc can be older.

Scale heights for observed discs are usually quoted for an exponential profile, rather than for a sech^2 profile. In order to compare the scale heights of the new thin disc and the thickened old disc to observations, we compute the exponential scale heights of the final discs in our MBh run. The exponential scale height of the new thin disc is $h_{\text{new}} = 0.35$ kpc

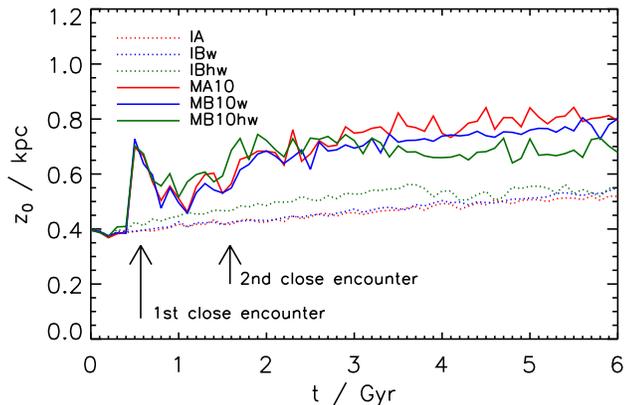


Figure 4. Evolution of the disc scale height for isolated and 1:10 merger simulations with and without a gaseous halo for the case with galactic winds.

and that of the old thick disc is $h_{\text{old}} = 0.6$ kpc. These values are in very good agreement with the observational constraints (cf. the compilation presented in Chang et al. 2011).

To test the possibility for this scenario further, we compute the velocity dispersions of the old thick disc and the new thin disc at the solar radius. For the MBh run the velocity dispersion ellipsoid of the old thick disc is $(\sigma_r, \sigma_\phi, \sigma_z) = (62, 44, 33) \text{ km s}^{-1}$, while for new thin disc it is $(\sigma_r, \sigma_\phi, \sigma_z) = (52, 36, 22) \text{ km s}^{-1}$. These values are in good agreement with observations by Soubiran et al. (2003), who find $(\sigma_r, \sigma_\phi, \sigma_z) = (63, 39, 39) \text{ km s}^{-1}$ for the thick disc and $(\sigma_r, \sigma_\phi, \sigma_z) = (39, 20, 20) \text{ km s}^{-1}$ for the thin disc. Finally we note that the velocity dispersions in our simulation increase with stellar age, in agreement with observations (Wielen 1977; Nordström et al. 2004; Seabroke & Gilmore 2007). For star with an age of 1 Gyr we get $(\sigma_r, \sigma_\phi, \sigma_z) = (41, 29, 15) \text{ km s}^{-1}$, while for stars with an age of 6 Gyr we get $(\sigma_r, \sigma_\phi, \sigma_z) = (62, 44, 33) \text{ km s}^{-1}$, consistent with the observed values. This suggests that a scenario is very plausible, in which the thick disc results from the thickening of an initial disc through a minor merger and the thin disc is formed after this merger from accretion of gas from the halo and subsequent star formation.

3.3 The effects of galactic winds

In the following we study the evolution of the scale height during the simulations that include galactic winds. The results are shown in Figure 4 for isolated and 1:10 merger runs. When winds are included, the isolated simulation with only 20 percent cold gas in the disc (and no gaseous halo, IBw) shows more thickening than in the case without winds (IB), leading to a final scale height that is even slightly larger than in the dissipationless simulation (IA). If the hot gaseous halo is included, the scale height increases even more quickly than in the simulations without a hot halo, up to a value of $z_0 = 0.55$ kpc at $t \sim 4$ Gyr after which it is roughly constant. After 6 Gyr all isolated runs converge to the same scale height.

The scale height of the 1:10 merger simulation with winds and without a gaseous halo (MBw) shows considerably more thickening than the run without winds (MB). With $z_0 = 0.77$ kpc, it has almost the same final scale height

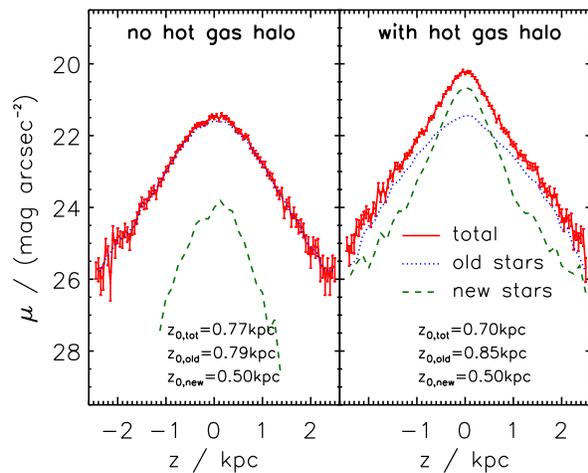


Figure 5. Final edge-on surface brightness profiles for the 1:10 merger simulations with winds at a projected radius of 8 kpc for old, new, and all stars.

as the dissipationless run (MA). Even if the hot gaseous halo is included in the simulation, the final scale height is much larger than the final scale height of the isolated dissipationless simulation with $z_0 = 0.7$ kpc. In contrast to the simulations without galactic winds, we find that a 1:10 merger leads to a considerable increase of the scale height, producing discs with final scale heights of $z_0 \gtrsim 0.7$ kpc. We conclude that in order to be able to retain very thin discs, the efficiency of galactic winds has to be rather low.

We further investigate what is causing the increased scale heights when galactic winds are considered. There are two possible mechanisms that can lead to a thicker disc. One explanation is that if winds are included the SFR is lowered, resulting in a less massive new disc at the end of the simulation. Since the dominant effect in the run without winds (but including a gaseous halo) is the reformation of a massive new thin stellar disc that dominated the overall surface density profile, a less massive disc will result in a smaller contribution by the new disc to the total scale height. This leads to a larger contribution due to the thickened old disc and thus to a larger scale height. Another possibility is that the winds actually alter the mass distribution in the cold gas disc. As the outflow of gas exerts a pressure force on the cold gas component, the density in the galactic plane is lowered, resulting in a shallower $\rho(z)$ profile for the gaseous disc. This, in turn, leads to a shallower profile for the new stellar disc and thus to a larger scale height for the total stellar disc.

In order to study which of these effects is more important, we determine the SFR and the stellar mass of the new stellar disc for the simulations with winds and present the results in the right panels of Figure 3. Due to the winds, the SFR is indeed lowered and has a constant value of $\sim 5M_\odot \text{ yr}^{-1}$ for the simulations with a hot gaseous halo. The final stellar mass of the new stellar disc is therefore lower than the mass of the old stellar disc (even if hot gas is included) and has only about half of the value that is obtained without winds. As a result, the new stellar disc is less dominant in the case with winds and the old stellar disc has a larger influence on the total scale height.

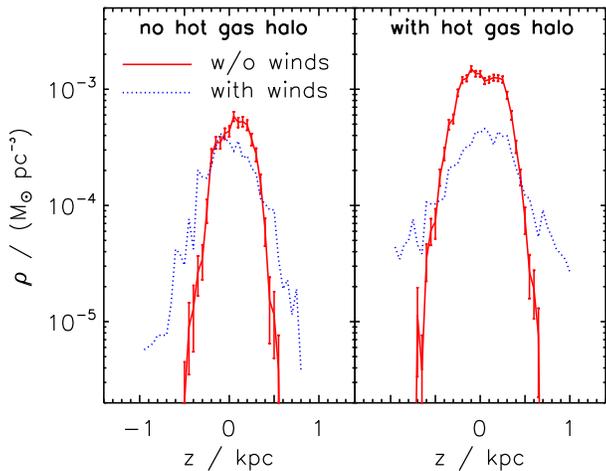


Figure 6. Final 3d density profiles for the cold gaseous discs in the 1:10 merger simulations at a radius of 8 kpc. The simulations without winds are given by the solid lines while the runs with winds are given by the dotted lines.

This can also be seen in the edge-on projected surface brightness for old, new and all stars. The profiles are presented in Figure 5 for the runs without hot gas (left panel) and including the gaseous halo (right panel). Due to the very low SFR in the case where the hot halo is neglected, the new stellar component has much less mass than the old one. Therefore the surface brightness is completely dominated by the old stellar disc and the total scale height has a relatively large value of $z_0 = 0.77$ kpc. If the hot gaseous halo is included, the new stellar disc is much more massive. However, due to the winds, its final mass is still lower than the mass of the old stellar disc. Therefore the new stellar component dominates the surface brightness only close to the galactic plane and the final total scale height ($z_0 = 0.7$ kpc) is much larger than for the windless case. This shows that the effect caused by a lowered SFR and stellar mass because of the winds has a large impact on the scale height.

We also investigate whether the shallower gas potential due to the pressure forces of the winds also affects the final scale height. To this end, we compute the 3d gas density as a function of distance from the galactic plane at a radius of R_{\odot} . The resulting profiles are shown in Figure 6 for the runs without a hot component (left panel) and for the runs with a gaseous halo (right panel). These results clearly show that in the simulations with galactic winds the vertical density profile of the gas is much shallower than in the runs without winds. Especially in the simulation with a gaseous halo, the wind forces have pushed the cold gas to larger distances from the plane, such that there is less material close to the disc plane. This, in turn, also affects the profile of the new stellar discs that form from these gaseous discs. Comparing the runs without winds (Figure 2) to those with winds (Figure 5), we find that the new stellar discs also have a shallower profile in the runs with winds. As a result, the new disc in the run without hot gas and with winds (MB10w) has a larger scale height of $z_{0,new} = 0.5$ kpc compared to the run without winds (MB10) with $z_0 = 0.4$ kpc. Similarly, the run with a hot gaseous halo and with winds (MB10hw) has a larger scale height of $z_{0,new} = 0.5$ kpc compared to the run without winds (MBh10) with $z_0 = 0.45$ kpc. Due to the

larger scale heights of the new stellar discs, the scale heights of the total stellar discs are also larger.

The last question that has to be addressed for the simulations with winds is, how much each of the two effects contribute to the larger scale heights. If we look at the evolution of the scale height in the isolated run with winds and hot gas (IBhw), we see that z_0 increases more quickly than in the isolated simulation without winds. Since there is no merger event, the scale heights of the old stellar discs evolve similarly for IBh, IBhw and even IA. This means that the increase of z_0 in IBhw can only be due to the evolution of the new stellar disc. If the effect of a shallower gas profile due to the wind forces was negligible compared to the effect of the lower SFR and stellar mass, the scale height of the IBhw run should have a value between those of the IBh run (maximum new stellar mass) and the IA run (no new stellar mass). However, the scale height of the IBhw run is always larger than the others. This indicates that the effect of a thicker new stellar disc leads to this increase of z_0 of the order of $\Delta z_0 \sim 0.05$ kpc. This result is in agreement with the finding that the new stellar disc has a scale height that is roughly $\Delta z_0 \sim 0.05$ kpc larger when winds are considered. We thus conclude that the scale height can increase by roughly $\Delta z_0 \sim 0.05$ kpc due to the effect of the shallower potential caused by the wind forces.

On the other hand, this value cannot explain the values of the scale height in the 1:10 merger simulations. The difference in scale height between the run with a hot halo and winds (MB10hw) and without winds (MB10h) is of the order $\Delta z_0 \sim 0.2$ kpc. This means that this large difference can only be explained by the lower stellar mass in the run with winds, such that the thickened old disc still dominates the overall surface brightness profile. We thus conclude that the more important effect driving the increase of the scale height when winds are considered comes from the lower contribution of the new thin stellar disc due to the lowered SFR. The shallower profile of the gaseous disc caused by the wind forces has a comparably minor impact.

3.4 Resolution study

Since galactic discs are fragile systems, the morphology of numerical realizations of discs can potentially be modified simply by numerical effects, e.g. through bar formation or flaring. Therefore, it is important to check how the evolution of the disc morphology changes if the numerical resolution is altered. To this end we compare the results obtained with our standard resolution to those obtained with an increased resolution as employed by M10. These high resolution runs have twice the number of dark matter and old stellar particles and four times the number of gas particles in the initial conditions compared to our standard resolution. This implies that the number of new stellar particles is also four times higher.

First, the stability of the initial disc is a key point to be addressed before attempting to study the effects of satellite mergers. We compare the runs for the isolated disc with an initial value of 20 percent cold gas in the disc, neglecting both the hot gas and galactic winds (IB). The results are presented in Figure 7. While for the standard resolution run the scale height increases to a final value of $z_0 = 0.5$ kpc (from an initial value of $z_0 = 0.4$ kpc), the high resolu-

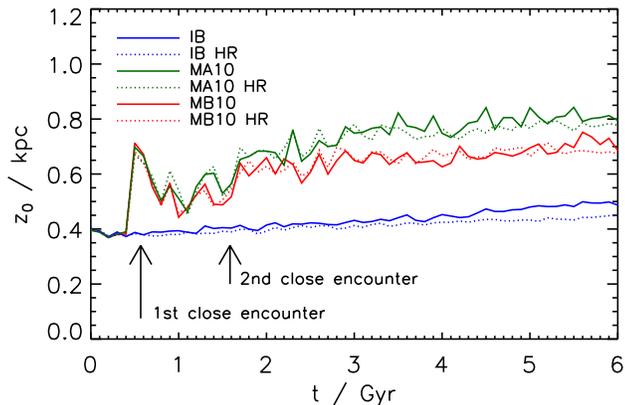


Figure 7. Comparison of the evolution of the scale height between the runs with standard resolution (solid lines) and resimulations with higher resolution (dotted lines) for the isolated and 1:10 merger simulations without a hot gaseous halo and without galactic winds.

tion run shows less thickening with a final scale height of $z_0 = 0.45$ kpc. This shows that for the isolated disc systems the stability is affected by numerical resolution, although the difference between the standard and the high resolution runs is small. The total amount of thickening due to numerical effects is very low compared to the thickening due to satellite accretion events, even for the standard resolution. This implies that any further increase in z_0 is due to accretion events.

For the 1:10 merger simulations we do not find a difference between the standard and high resolution runs. For both cases the scale height is increased to the same value during the first two encounters and evolves only slightly thereafter. Thus, if the discs are thickened during a merger to scale heights of $z_0 \lesssim 0.6$ kpc, their further evolution is the same for both resolutions. The reason for this is that thicker discs are more robust to heating (Kazantzidis et al. 2009). This means that for our merger runs, our chosen resolution is sufficient, i.e. we achieve numerical convergence.

Finally, we compare the results for the standard and high resolution runs for the 1:10 merger that includes both the hot gaseous halo and galactic winds (MB10hw). The resulting evolution of the scale heights is shown in Figure 7. The results for the two runs agree extremely well. For both simulations the scale height reaches a maximum value after the second encounter and decreases again. We therefore conclude that the effects of the hot gaseous halo and the galactic winds are captured well with our standard resolution and that also in this case, numerical convergence is achieved.

4 RESULTS FOR THE 1:5 MERGER

In section 3 we have shown that depending on the mass of the hot gaseous halo and the efficiency of stellar driven winds or other feedback processes, a MW-like galaxy can experience a 1:10 merger without being thickened with respect to an isolated simulation. In this section we study the impact of a larger mass ratio 1:5 merger. As before we run merger simulations for a dissipationless disc system (MA5),

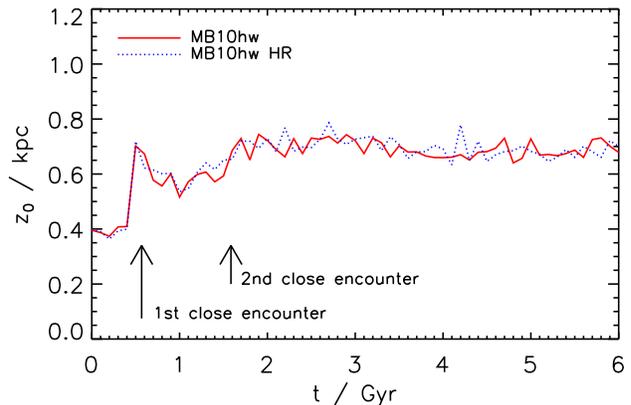


Figure 8. Comparison of the evolution of the scale height between the 1:10 merger run with standard resolution (solid line) and the resimulation with high resolution (dotted line) for the simulations including a hot gaseous halo and galactic winds.

a disc galaxy that contains an initial value of 20 percent cold gas in the disc (MB5) and a system that also includes a hot gaseous halo (MB5h).

The resulting evolution of the scale height for the 1:5 merger simulations without galactic winds is shown in Figure 9. In the run without gas, the disc is strongly thickened with a final scale height of $z_0 = 1$ kpc. This implies that the thin stellar disc is completely destroyed and only a thick disc is left, leading to the conclusion that the thin disc of a MW-like galaxy cannot survive a dissipationless 1:5 merger. If the initial disc contains 20 percent cold gas, the thickening is considerably reduced with a final scale height of $z_0 = 0.85$ kpc. Similar to the 1:10 merger, the cold gas in the disc absorbs some of the impact energy of the satellite and is able to radiate it away, such that the amount of thickening during the first two encounters is reduced. After the second encounter, the scale height is relatively constant, so the effects of the new stellar disc forming from the cold gas are very small. If the hot gas in the halo is also considered, the amount of thickening is greatly reduced. The final scale height of $z_0 = 0.6$ kpc is only slightly larger than that in the isolated simulation. The resulting system thus has a scale height that is consistent with that of observed MW-like galaxies. We therefore conclude that if enough hot gas can cool and form stars, a MW-like system is able to have a thin disc even after a 1:5 merger.

If we also consider the galactic winds, the final scale heights of the simulations with gas increase with respect to the windless case, in agreement with the results we obtained for the 1:10 merger simulations. The run that includes only gas in the disc (MB5w) shows the same evolution of the scale height as the dissipationless run. The reason for this is the very small SFR and resulting mass of the new stellar disc, such that its contribution to the final surface brightness profile is negligible. Moreover, the amount of cold gas is reduced considerably by the winds, so that the lower mass gas disc cannot absorb impact energy. The simulation with winds and only gas in the disc is therefore similar to a dissipationless run.

If the hot gaseous halo is included (MB5hw), the scale height increases during the first two encounter and then decreases again to a final value of $z_0 = 0.8$ kpc. Again, due to

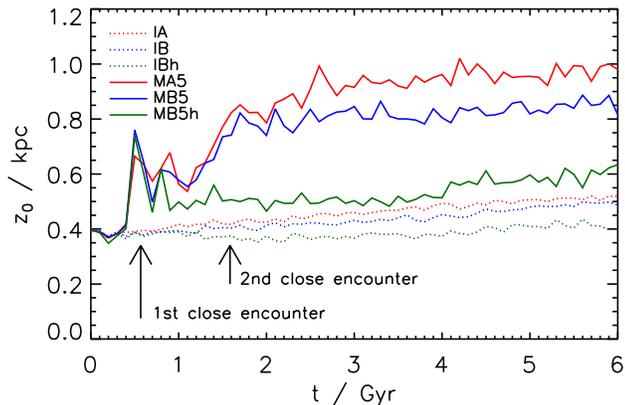


Figure 9. Evolution of the disc scale height for isolated and 1:5 merger simulations with and without a gaseous halo for the case without galactic winds.

the winds, the gas fraction during the first two encounters is reduced, such that the amount of impact energy that can be absorbed is very small. As a result, this simulation behaves in a similar manner as a collisionless run at the beginning of the run. However, after the disc has been thickened, the mass of the new stellar disc grows and starts to affect the total surface brightness profile. As the new disc becomes comparable in mass to the old stellar disc, the total scale height decreases again. However, as the stellar mass of the new disc is much lower than in the windless case, the final scale height is still much higher. Nevertheless, even if galactic winds are operating, a MW-like galaxy can experience a 1:5 merger that leads to a system that is in the observable range of scale heights. We conclude that, if there is enough hot gas available in the halo and the wind efficiencies are very high, a disc system of the size of the MW can survive a 1:5 merger, without being in conflict with observational constraints.

5 CONCLUSIONS AND DISCUSSION

We investigated the role of a cooling gaseous halo in minor merger simulations using the parallel TreeSPH-code GADGET-2. For this we followed M11 and extended the initial conditions to include a hot gaseous halo (in addition to a dark matter halo, a stellar bulge and a disc consisting of stars and cold gas). We adopted the observationally motivated β -profile and demanded that the halo be in hydrostatic equilibrium. Furthermore the gaseous halo is rotating around the spin axis of the disc. We have fixed its angular momentum by requiring that the specific angular momentum of the gas halo is a multiple α of the specific angular momentum of the dark matter halo and treated α as a free parameter. We then fixed the value of α by requiring our simulations to reproduce the observed size-mass relation for galactic discs (see M11). We fixed the mass of the gaseous halo by requiring that the baryonic fraction within the virial radius is 85 percent of the universal one. As discussed in detail in M11, our adopted gaseous haloes are not in conflict with X-ray observations of MW-like spiral galaxies.

We have revisited the question of whether thin discs like the one observed in the MW can survive minor merger

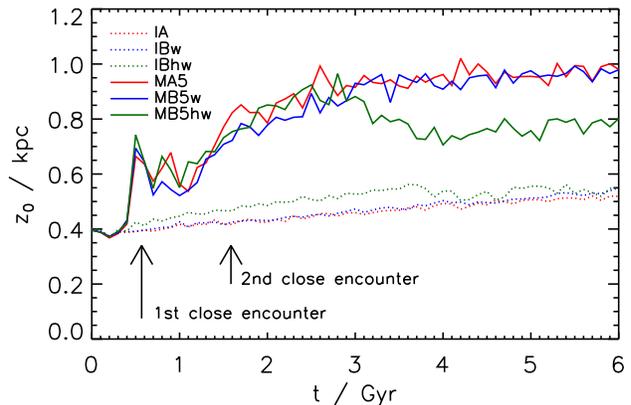


Figure 10. Evolution of the disc scale height for isolated and 1:5 merger simulations with and without a gaseous halo for the case with galactic winds.

events. In collisionless simulations of a 1:10 merger, such a disc is thickened considerably ($z_0 = 0.8$ kpc), while M10 have shown that if the cold gas component in the disc is considered, the thickening due to the merger can be reduced ($z_0 = 0.7$ kpc). The reason for that is the absorption of impact energy by the gas. Here, we have extended this study in order to also consider the hot gas component in the halo and found that the thickening with respect to collisionless simulations is further reduced, leading to a similar scale height as in an isolated run ($z_0 = 0.5$ kpc). This is due to the cooling and accretion of new cold gas which leads to the formation of a new thin disc. Similar to the conclusions reached in major merger simulations, we find that high disc cold gas fractions of ~ 40 percent are not needed in order to form realistic galaxies with properties as found in observations. The subsequent cooling of the gaseous halo compensates for lower initial cold gas fractions. We conclude that if a considerable amount of hot gas is available in the halo, a MW-like disc system can survive a 1:10 merger as a new thin disc reforms after the merger.

The regrowing thin disc can reduce the final scale height in two ways. First, the additional potential can cause heated stars to recontract towards the disc plane. Second, the new thin stellar disc is more massive than the old disc and therefore dominates the surface brightness profile leading to a lower overall scale height. We have shown that in our simulations the old stellar disc does not recontract, i.e. its scale height is not lower than in a merger simulation without gas. Therefore this effect cannot explain the small scale height of the total disc. Instead, we have demonstrated that the massive new stellar disc dominates the surface brightness profile resulting in a smaller overall scale height. Due to the subsequent cooling from the halo and star formation, the new disc is much more massive than in simulations that only have gas in the disc.

In the scenario presented in this work, the thick disc is the old stellar disc that has been thickened in a minor merger at $z \gtrsim 1$, while the thin disc is the new stellar disc that reforms after this merger. In the simulation with a hot gaseous halo, the mean stellar ages of the thin and thick discs in the solar neighborhood are ~ 4 Gyr and $\gtrsim 6$ Gyr, respectively, in agreement with measurements in the MW. We found an exponential scale height for the new thin disc of

$h_{\text{new}} = 0.35$ kpc and for the old thick disc of $h_{\text{old}} = 0.6$ kpc in very good agreement with the values obtained for the MW. Moreover we measured a velocity dispersion ellipsoid for the old thick disc of $(\sigma_r, \sigma_\phi, \sigma_z) = (62, 44, 33)$ km s⁻¹ and for new thin disc we found $(\sigma_r, \sigma_\phi, \sigma_z) = (52, 36, 22)$ km s⁻¹. The good agreement with observed values suggests that this scenario for the formation of the thin and thick discs is very plausible.

We have addressed the effects of galactic winds on the results of our simulations and found that if winds are included, the final scale heights are considerably larger. There are two effects the winds can have on the evolution of the scale height. On the one hand, the efficiency of gas cooling from the hot component and star formation partially depend on the feedback mechanism implemented in the simulations. If the winds are very efficient, the cooling rate and the SFR are lowered, resulting in a less massive new thin disc. In this case the thickened old stellar disc still dominates the surface brightness and the total scale height is larger. On the other hand, winds can exert a pressure force on the cold gas in the disc. This leads to an expansion of the cold gas and thus to a shallower profile. This in turn, results in a thicker new stellar disc and thus in a larger overall scale height.

To test how much each of these processes contributes to the increased scale heights when winds are present, we have performed a series of simulations with and without winds. In order to check whether the pressure forces of the winds have an effect on the profile of the gas, we computed the 3d density profile of the cold gas for the case with and without winds. We found that the cold gas profile $\rho(z)$ is indeed much shallower when winds are included. This, in turn, affects the thickness of the new stellar disc that forms from this gaseous disc. The scale height of the new disc is therefore roughly ~ 0.05 – 0.1 kpc larger when winds are present. Moreover the galactic winds reduce the SFR by a factor of ~ 2 , resulting in a new stellar disc that is less massive than the old one. The new disc then only dominates the surface brightness very close to the disc plane, and the scale height is fixed by the thicker old disc. This effect can lead to a scale height that is roughly ~ 0.2 kpc larger when winds are operating. We therefore conclude that lowered SFR has a larger impact on the evolution of the scale height than the pressure force exerted by the winds.

For all merger simulations with galactic winds we used the ‘constant wind’ model of Springel & Hernquist (2003), where the mass-loss rate driven by the winds is proportional to the SFR and the wind speed is constant. However, this simple assumption does not lead to very good agreement with observations such as the stellar mass vs. metallicity relationship for galaxies. Wind models in which the mass loading factor and wind velocity scale with galaxy internal velocity, motivated by the expected scalings for momentum driven winds, produce much better agreement with these observational scaling relations (Oppenheimer & Davé 2006). However, the wind speeds and the mass loading factor for MW-like galaxies in this model do not vary much after $z = 1$. Since the minor mergers that increase the disc scale height are expected to occur at low redshift and there is no star forming component associated with the satellite, we are fairly confident that a more sophisticated wind model would leave our qualitative results unchanged.

We have further tested the numerical convergence of our

models. To do this, we have employed simulations with twice the resolution in dark matter and old stars and four times the resolution in gas and new stars. Comparing our standard resolution simulations to the high resolution ones we found no difference in the evolution of the scale height during 1:10 mergers and only a small difference in the isolated runs. This shows that numerical convergence has been achieved and that any further increase in z_0 with respect to an isolated simulation is caused by a merger event.

The simulations for the 1:10 merger showed that a MW-like galaxy can have a thin disc after such an event without showing excessive heating if enough hot gas is available from which new gaseous and stellar discs can reform. In the light of this, we addressed the question whether such a galaxy can also have a thin disc after a 1:5 merger. To this end, we performed a suite of simulations with and without a hot gas component and galactic winds. We found that in a collisionless 1:5 merger simulation, the disc is thickened to a final value of $z_0 = 1$ kpc, i.e. the thin disc is destroyed. If an initial value of 20 percent cold gas is included in the disc, this thickening can be slightly reduced to a final value of $z_0 = 0.85$ kpc. However, if the hot gaseous halo is included, the final scale height is much smaller ($z_0 = 0.6$ kpc) and only slightly larger than in an isolated run. The reasons for this reduced thickening are the same as for the 1:10 merger. If both hot gas and galactic winds are considered, the final scale height after a 1:5 merger is $z_0 = 0.8$ kpc. Our simulations show that a MW-like galaxy can have a thin and a thick disc after such a merger if there is enough hot gas available in the halo and if the wind efficiency is low.

We found that the final scale heights in our simulations depend on the mass of the hot gaseous halo, the efficiency of the winds and the merger ratio. The values of the scale height in our post-merger sample are in the range $0.5 \lesssim z_0 \lesssim 1.0$ kpc. In the light of these results, we can assess whether our simulated systems are in agreement with observational findings, or whether the scale heights in our simulations present a problem for the CDM theory. Obtaining statistically unbiased observational measurements of scale heights for a complete sample of galaxies is difficult, due to small sample sizes, dust extinction and inclination effects. However, there are a considerable number of studies focusing on the vertical structure of galaxies (Shaw & Gilmore 1989, 1990; de Grijs & van der Kruit 1996; de Grijs et al. 1997; Pohlen et al. 2000; Kregel et al. 2002; Bizyaev & Kajsin 2004). These studies suggest that the majority of observed MW-like galaxies have scale heights in the range of $0.6 \lesssim z_0 \lesssim 1.0$ kpc. The statistical studies by Schwarzkopf & Dettmar (2000) and Yoachim & Dalcanton (2006) find that the distribution of scale heights for disc galaxies of the same mass as the MW is between 0.4 and 1.2 kpc with a maximum around ~ 0.6 – 0.8 kpc. The scale heights of our sample fall into this range. We therefore conclude that our simulations are in good agreement with observational findings.

This work underlines once again the importance of the inclusion of a dissipational component in galaxy merger studies. This component, even though subdominant from a gravitational point of view, is able to strongly modify the dynamical response of the stellar disc during minor mergers, making them more resistant against heating. Once both cold and hot gas are taken into account, claimed tensions

between the hierarchical model and the abundance of thin disks in the local Universe appear to be relaxed.

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