On the morphologies, gas fractions, and star formation rates of small galaxies

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ABSTRACT
We use a series of $N$-body/smoothed particle hydrodynamics simulations and analytic arguments to show that the presence of an effective temperature floor in the interstellar medium at $T_F \sim 10^4$ K naturally explains the tendency for low-mass galaxies to be more spheroidal, more gas rich, and less efficient in converting baryons into stars than larger galaxies. The trend arises because gas pressure support becomes important compared to angular momentum support in small dark matter haloes. We suggest that dwarf galaxies with rotational velocities $\sim 40$ km s$^{-1}$ do not originate as thin discs, but rather are born as thick, puffy systems. If accreted on to larger haloes, tenuous dwarfs of this kind will be more susceptible to gas loss or tidal transformation than scaled-down versions of larger spirals. For a constant temperature floor, pressure support becomes less important in large haloes, and this produces a tendency for massive isolated galaxies to have thinner discs and more efficient star formation than their less-massive counterparts, as observed.

Key words: hydrodynamics – methods: analytical – methods: $N$-body simulations – galaxies: dwarf – galaxies: formation.

1 INTRODUCTION
It is well established that small galaxies have longer star formation time-scales than their larger cousins (e.g. Hunter & Gallagher 1985; van Zee 2001; Kauffmann et al. 2003; Brinchmann et al. 2004; Geha et al. 2006). Dwarf galaxies in the field have higher specific gas fractions (van Zee 2001; Geha et al. 2006) and are morphologically thicker (Dalcanton, Yoachim & Bernstein 2004; Yoachim & Dalcanton 2006) than luminous late-type galaxies. It is common to discuss supernova feedback or radiative feedback as a means to explain these trends (e.g. Dekel & Silk 1986; White & Frenk 1991; Kauffmann, White & Guiderdoni 1993; Bullock, Kravtsov & Weinberg 2000; Mayer et al. 2001a; Somerville 2002; Dekel & Woo 2003; Kravtsov, Gnedin & Klypin 2004; Read, Pontzen & Viel 2006; Stinson et al. 2006), yet the origin of the observed relations between galaxy properties and their total mass remains open for debate.

In this paper, we investigate the simple systematic effect that a gas temperature floor, $T_F$, has on the star formation efficiencies, gas fractions, and morphologies of galaxies as a function of dark matter halo mass. We show that even a moderate effective temperature floor of $T_F \simeq 10^4$ K, as might arise naturally in the presence of a photoionizing background, produces many of the general trends observed. Specifically, pressure support becomes dynamically com-
smallest galaxies in the universe (e.g. Bullock et al. 2000; Benson et al. 2002; Strigari et al. 2007). In a recent examination, Hoef et al. (2006) used cosmological simulations with cooling and star formation to show that gas at typical galactic densities will have equilibrium temperatures \(\sim (1-3) \times 10^3 \, \text{K}\), and that this temperature is fairly insensitive to the normalization of the UV flux. This heating strongly suppresses the baryon fraction in haloes smaller than \(\sim 20 \, \text{km s}^{-1}\) in their simulations. Our investigations focus on galaxies that are just above this scale. Specifically, we explore the morphology and star formation efficiency (SFE) of galaxies that are large enough to accrete warm gas but small enough to be dynamically affected by warm gas pressure.

We note that the effect of a finite temperature floor on dwarf galaxy formation was discussed in a semi-analytic context by Kravtsov et al. (2004), who used the idea to motivate models for low star formation rates in small galaxies, and by Tassis, Kravtsov & Gnedin (2004), who used a similar model to investigate the gas fraction and mass–metallicity relationships in dwarf galaxies. Taylor & Webster (2005) studied star formation within equilibrium dwarf galaxies by modelling \(\text{H}_2\) cooling within a thermally balanced \(\sim 10^4 \, \text{K}\) medium and derived lower limits on self-regulated star formation rates in dwarfs in this context.

In the next section, we present an analytic investigation into the importance of baryonic pressure support compared to angular momentum support as a function of virial mass and gas temperature and show that pressure support should become dynamically important in dwarf galaxy haloes. In Section 3, we use the \(N\)-body/smoothed particle hydrodynamics (SPH) code GASOLINE (Wadsley, Stadel & Quinn 2004) to explore galaxy formation with a range of temperature floors and halo masses. We present results on the galaxy disc thickness, gas fractions, and star formation rates as a function of galaxy circular velocity. We reserve Section 4 for discussion and Section 5 for conclusions.

2 ANALYTICAL EXPECTATIONS

The standard analytic approach for calculating galaxy sizes and morphologies within dark matter haloes assumes that the gas cools to a temperature well below the halo virial temperature, \(T_v \ll T_c\). As a result, the thermal pressure support in the gas is small compared to its angular momentum support. A thin disc of star-forming material is the natural outcome (Fall & Efstathiou 1980; Blumenthal, Faber & Primack 1986). This thin-disc configuration is taken to be the starting point for galaxy formation (and star formation) in most models, including those that model dwarf galaxies (e.g. Kauffmann et al. 1993; Somerville & Primack 1999; Benson et al. 2002; Somerville 2002; Mastropietro et al. 2005; Gnedin et al. 2006; Mayer et al. 2006; Dutton et al. 2007). Here, we stress that the thin disc approximation should break down in small haloes where \(T_v \gg T_c \sim 10^4 \, \text{K}\). In these cases, the pressure support radius becomes comparable to the angular momentum support radius and we expect a thick morphology. What follows is a simple analytic investigation aimed at quantifying the halo mass scale of relevance. A more rigorous numerical approach is given in the next section.

Consider dark matter haloes of mass \(M_h\) with virial radii defined\(^1\) such that \(R_v \simeq 113 \, \text{kpc}\) \((M_h/10^{11} \, M_\odot)^{1/3}\). We assume that halo density profiles are well approximated by the NFW fit (Navarro, Frenk & White 1996):

\[
\rho(r) = \frac{\rho_s}{x(x+1)^2},
\]

where \(x = r/r_s\) and the scale radius, \(r_s\), is determined from the halo concentration parameter \(c_v \equiv R_s/r_s\). We adopt the relation \(c_v = 10 \, (M_h/10^{11} \, M_\odot)^{-0.086}\), which is appropriate for a \(\sigma_z = 0.75 \, \text{km s}^{-1}\) cold dark matter (ΛCDM) cosmology (Bullock et al. 2001a; Macciò et al. 2007). Given \(M_h\) and \(c_v\), the circular velocity curve, \(V_c^2(r) = GM(r)/r\), is determined by the integrated mass profile. For our adopted relation, the circular velocity peaks at a maximum value \(V_{\text{max}} \simeq 71 \, \text{km s}^{-1}\) \((M_h/10^{11} \, M_\odot)^{1/3}\).

In the standard thin-disc scenario, the gas obtains specific angular momentum that is similar to that of the dark matter, which is often characterized by a dimensionless spin parameter (Peebles 1969) defined as \(\lambda \equiv j/|E|^{1/2}L^{-1/2}\), where \(G\) is Newton’s constant and \(j\) and \(E\) are the specific angular momentum and energy of the halo, respectively. Simulated CDM haloes typically have \(\lambda \sim 0.03\) with a 90 per cent spread between 0.01 and 0.1 (e.g. Barnes & Efstathiou 1987; Bullock et al. 2001b; Macciò et al. 2007).

It is straightforward to show that if the gas cools and contracts without angular momentum loss to form a thin, angular momentum supported exponential disc, the disc scale radius is given by Mo et al. (1998, hereafter MMW):

\[
R_d = \lambda \, R_{\text{halo}} \, f(c, \lambda, m_d).
\]

Here, we assume that the gas falls in from a radius \(R_{\text{halo}}\), defined to be either the virial radius, \(R_v\), or the ‘cooling radius’, \(R_c\), depending on which one is smaller, \(R_{\text{halo}} = \min(R_v, R_c)\). By introducing the cooling radius (White & Frenk 1991), we account for the expectation that hot gas in the outskirts of massive haloes will not have had time to cool since the halo formed. For simplicity, we adopt\(^2\) \(R_c = 129 \, \text{kpc} \, V^{-1/2}\), where \(V_{\text{max}}\) is the halo maximum circular velocity in units of \(120 \, \text{km s}^{-1}\). The function \(f(\sim 1)\) in equation (2) contains information on the halo profile shape and contraction from baryonic infall, and depends on the initial halo concentration \(c = R_{\text{halo}}/R_v\) and the disc mass, \(m_d\), in units of the total mass within \(R_{\text{halo}}\).

The three solid lines labelled with \(\lambda\) values in Fig. 1 show \(R_d\) calculated in the standard thin-disc framework as a function of the (initial) halo \(V_{\text{max}}\) value. From top to bottom panel, the lines assume spin parameters \(\lambda = 0.1, 0.03\) and 0.01. We have used the fitting formula from MMW \(f(c, \lambda, m_d)\) with \(m_d = 0.1\). We plot the scale radius as a function of the initial, uncontracted halo \(V_{\text{max}}\) in order to facilitate the following comparison.

Consider now the galaxy radius that would result from pressure support in an idealized, spherically symmetric system consisting of a gravitationally subdominant gas. Assume that this gas has no angular momentum but reaches a temperature of \(T_v = T_v^c\) within an extended NFW halo of virial temperature \(T_v\). We emphasize that we will calculate the pressure support radius for ‘cold’ gas at \(T_v = T_v^c\), the lowest temperature the gas can reach within our assumptions. For this approximate calculation, we neglect baryonic contraction. We will define the virial temperature in analogy with an isothermal gas of temperature \(T\) and its associated speed of sound \(c_s\) (e.g. Maller & Bullock 2004):

\[
T = 10^4 \, K \left(\frac{c_s}{11.5 \, \text{km s}^{-1}}\right)^2.
\]

\(^1\) In our definition, the virial radius contains an average mass density equal to 360 times the matter density of the universe and we adopt \(\Omega_m = 1 - \Omega_\Lambda = 0.27\) and with \(h = 0.7\).

\(^2\) This approximation was given by Maller & Bullock (2004) for haloes with \(V_{120} > 1\). Below this scale, the virial radius sets \(R_{\text{halo}}\).
Specifically, $T_c$ is set by using $V_{max}/\sqrt{2}$ for $c_1$ in equation (3).

The equilibrium gas profile, $\rho_g(r)$, will be set by a competition between the isothermal gas pressure, $P_g = c_1^2 \rho_g$, and the gravitational potential. If we assume that the gravitational force is dominated by the NFW halo potential, the hydrostatic force balance equation $c_2^2 \frac{d\rho_g}{dr} = -\frac{V^2(r)}{r}$ can be rewritten in terms of the dimensionless radial parameter $x = r/r_s$ as

$$1 \frac{d\rho_g}{dx} = -\eta h(x).$$

Here, $\eta = T_c/T_F$ parametrizes the relative strength of the halo gravity and the thermal pressure of the gas and $h(x) = 9.26 x^{-1}[\ln(1 + x) - x/(1 + x)]$. Note that in the limit of large $\eta (T_v \gg T_F)$, the gas profile will be centrally concentrated with a large negative derivative, and a negligible pressure support radius. More generally, solving equation (5) for $\rho_g$ yields

$$\rho_g(x) = \rho_0 \exp \left\{ -9.26 \eta \left[ 1 - \frac{\ln(1 + x)}{x} \right] \right\},$$

where the normalization parameter $\rho_0$ sets the gas density at $x = 0$. It is clear that in small haloes with $\eta \sim 1$, the gas profile can extend to $x \sim 1$ or $r \sim R_{v}/c \sim 0.1 R_{v}$, which is comparable in size to the angular momentum support radius (equation 2).

The thick solid and dotted lines in Fig. 1 show a more explicit comparison for various gas floor temperatures: $T_F = 1.15$ and $5 \times 10^4$ K. We have used equation (6) to compute the radius $R^*$ that encloses 26 per cent of the pressure-supported galaxy mass as a function of the halo $V_{max}$. This radius is analogous to the scale radius for an exponential disc, which contains 26 per cent of the rotationally supported disc mass. While relatively unimportant in large Milky Way-size haloes ($V_{max} \sim 200$ km s$^{-1}$), we see that pressure support should dominate in shaping galaxy morphologies and gas distributions in small haloes. The expectation is that small galaxies will be intrinsically puffier than large galaxies, even in the absence of environmental influences.

The scale where pressure becomes important compared to rotation will naturally depend on the temperature floor of the gas and on the intrinsic spin. For $T_F = 1.5 \times 10^4$ K and $\lambda = 0.03$, we expect the effect to become very important for dwarf-size haloes with $V_{max} \lesssim 35$ km s$^{-1}$. If the temperature floor is high, $T_F = 5 \times 10^4$ K, then the effect could be important even in $\sim 100$ km s$^{-1}$ haloes if they have inhabited the low-spin tail of the distribution, $\lambda = 0.01$. If galaxies form with the range of spins expected ($\lambda \sim 0.01-0.1$), then we would predict a range of morphologies (from puffy to thin discs) at fixed $V_{max}$ as long as the temperature floor is roughly the same from galaxy to galaxy. Though we do not explore galaxy formation in very small haloes ($\lesssim 20$ km s$^{-1}$) in the rest of this paper, it is interesting to note that we expect the morphologies of the smallest objects to be essentially spheroidal, with initially extended gas profiles. The stellar sizes of these objects will likely be much smaller than the gas extent, as high densities will be required for star formation. This might provide an explanation for why the smallest galaxies [dwarf spheroidal galaxies (dSphs)] are always dispersion-supported systems.

The simple, spherical model we have just explored was primarily designed to guide expectations. Stronger results are presented in the next section, where we use three-dimensional hydrodynamical simulations to investigate the effect of a reasonable gas temperature floor on morphologies, gas fractions, and star formation rates in small galaxy haloes.

3 SMOOTHED PARTICLE HYDRODYNAMICS SIMULATIONS

We use the parallel TreeSPH code GASOLINE (Wadsley et al. 2004), which is an extension of the pure $N$-body gravity code P$^3$MORPH developed by Stadel (2001). It includes artificial viscosity using the shear-reduced version (Balsara 1995) of the standard Monaghan (1992) implementation. GASOLINE uses a compact kernel with no support for the softening of the gravitational and SPH quantities. The energy equation is solved using the asymmetric formulation, which is shown to yield very similar results compared to the entropy-conserving formulation but conserves energy better (Wadsley et al. 2004). The code includes radiative cooling for a primordial mixture of helium and (atomic) hydrogen. Because of the lack of molecular cooling and metals, the efficiency of our cooling functions drops rapidly below $10^4$ K. The lack of molecular cooling is unimportant in our investigation because we enforce temperature floors $T_F \geq 1.5 \times 10^4$ K.

We investigate runs with and without star formation. The adopted star formation recipe is similar to that described in Katz (1992). Specifically, a gas particle may spawn star particles if (i) it is in an overdense region; (ii) it is cool, with $T \equiv T_k$; and (iii) it has a density greater than a critical threshold, $\rho_{20} > \rho_{SF}$. In practice, the critical star formation density is the most important parameter. In our primary simulations, we use $\rho_{SF} = 2.5 \times 10^4 M_{\odot} h^{-1}$ kpc$^{-3}$, but explore a case with $\rho_{SF}$ increased by a factor of 100 in Section 4.

Once a gas particle is eligible for spawning stars, it does so based on a probability distribution function with an SFE factor $c^s$ that is tuned to match the Kennicutt–Schmidt law for the Milky Way-
M33-size discs described in Kaufmann et al. (2007). The mass of gas particles decreases gradually as they spawn more star particles. After its mass has decreased below 10 per cent of its initial value, the gas particle is removed and its mass is re-allocated among the neighboring gas particles. Up to six star particles are then created for each gas particle in the disc. We note that Stinson et al. (2006) have implemented a similar star formation recipe, although they include an allowance for supernova feedback effects using a subgrid, multiphase model based on blast waves.

### 3.1 Initial conditions

We simulate 15 isolated systems with masses spanning the scale of dwarf galaxies to large spirals, with initial maximum circular velocities that range from \( V_{\text{max}} = 24 \) to 148 km s\(^{-1}\). We also present results from an older simulation of a Milky Way-size galaxy (\( V_{\text{max}} = 168 \) km s\(^{-1}\)) that was originally discussed in Kaufmann et al. (2007). Haloes are initialized as spherical equilibrium NFW profiles using the methods outlined in Kazantzidis, Magorrian & Moore (2004) and we use the mass–concentration relationship discussed in Section 2 to set the profile parameters. Table 1 lists the specific parameters used in each simulation and provides a reference name for each run.

We initialize a fraction of the total halo mass, \( f_{\text{s}} = 0.1 \), as a hot baryonic component with the same radial distribution as the dark matter and impose a temperature profile such that the gas is initially in hydrostatic equilibrium with an adiabatic equation of state. For all of our fiducial models, we choose \( \lambda_{g} = 0.03 \) for our gas spin parameter, defined in analogy with the halo spin as \( \lambda_{g} \equiv j_{g} |E|^{1/2} G^{-1} M_{\odot}^{-3/2} \). Here, \( j_{g} \) is the average specific angular momentum of the gas, and \( E \) and \( M_{\odot} \) are the total energy and mass of the halo.

The specific angular momentum distribution of the gas is assumed to scale linearly with the cylindrical distance from the angular momentum axis of the halo, \( j \propto r^{1.0} \). This choice is consistent with values found for dark matter haloes within cosmological N-body simulations (Bullock et al. 2001b). For simplicity, we initialize the dark matter particles with no net angular momentum.

The hot gaseous halo is sampled with a ‘hot’ temperature floor at \( T_{\text{F}} = 10^{4} \) K. We performed two additional \( V_{\text{max}} = 53 \) km s\(^{-1}\) simulations with a ‘warm’ and a ‘hot’ temperature floor at \( T_{\text{F}} = 3 \) and \( 5 \times 10^{4} \) K, respectively, and simulated a second \( V_{\text{max}} = 41 \) km s\(^{-1}\) case with \( T_{\text{F}} = 3 \times 10^{5} \) K. Higher temperature floors were not explored in the smaller haloes because galaxy formation is suppressed altogether if \( T_{\text{F}} \sim T_{\text{F}} \).

The galaxies were evolved for 5 Gyr, but we find that the global results stabilize after 3 Gyr (see Fig. 6 below). The two largest ‘gas-only’ runs without star formation (G74.g and G148.g) produced gas discs that were unstable to their own self-gravity and became clumpy. This is not too surprising, given the low \( T_{\text{F}} \) adopted, and is consistent with previous claims that substantial heating of the ISM is

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**Table 1. Simulated galaxies**

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|-----|-----|-----|-----|-----|-----|-----|-----|
| Name | \( V_{\text{max}} \) (km s\(^{-1}\)) | \( c_{v} \) | \( M_{c} \) \( (10^{10} \text{M}_{\odot}) \) | \( T_{\text{F}} \) (10\(^{5}\) K) | \( R_{d} \) (kpc) | \( z_{d} \) (kpc) | \( V_{2.2} \) (km s\(^{-1}\)) |
| D24 | 24 | 14 | 0.29 | 1.5 | 0.30 | 0.08 | 37 |
| D24.g | 24 | 14 | 0.29 | 1.5 | 0.36 | 0.19 | 35 |
| D28 | 28 | 13 | 0.47 | 1.5 | 0.56 | 0.09 | 43 |
| D28.g | 28 | 13 | 0.47 | 1.5 | 0.51 | 0.18 | 41 |
| D41 | 41 | 12 | 1.6 | 1.5 | 0.90 | 0.10 | 65 |
| D41.g | 41 | 12 | 1.6 | 1.5 | 1.03 | 0.16 | 65 |
| D41.W | 41 | 12 | 1.6 | 3.0 | 0.61 | 0.13 | 64 |
| D53 | 53 | 11 | 3.8 | 1.5 | 1.29 | 0.12 | 84 |
| D53.g | 53 | 11 | 3.8 | 1.5 | 1.53 | 0.15 | 84 |
| D53.W | 53 | 11 | 3.8 | 3.0 | 1.05 | 0.16 | 82 |
| D53.H | 53 | 11 | 3.8 | 5.0 | 0.75 | 0.18 | 84 |
| G74 | 74 | 10 | 11.0 | 1.5 | 1.6 | 0.14 | 115 |
| G74.g | 74 | 10 | 11.0 | 1.5 | 2.41 | 0.03 | 92 |
| G148 | 148 | 8 | 100.0 | 1.5 | 1.95 | 0.22 | 209 |
| G148.g | 148 | 8 | 100.0 | 1.5 | 2.51 | 0.02 | 217 |
| G168.gHRLS | 168 | 11 | 115.0 | 3.0 | 2.46 | 0.13 | 213 |

Notes. Column 1: names labelled ‘-g’ refer to pure gas runs without star formation whereas names with ‘-W’ and ‘-H’ signify ‘warm’ or ‘hot’ temperature floors and ‘HRLS’ refers to the Milky Way model described in Kaufmann et al. (2007). Columns 2–4: the listed values for \( V_{\text{max}}, c_{v}, \) and \( M_{c} \) are initial halo parameters. Column 5: \( T_{\text{F}} \) is the imposed temperature floor. Columns 6–8: the last three columns list parameters measured in the final galaxy, where \( R_{d} \) and \( z_{d} \) are the exponential scalelength and scaleheight, respectively, and \( V_{2.2} \) is the rotational velocity in the gas measured at 2.2\( R_{0} \). Scaleheights marked with (*) are artificially large as a result of numerical heating. Gas disc parameters marked with (+) are derived from discs which have become Toomre unstable, thin, but spatially irregular.
needed to stabilize disc galaxies (e.g. Robertson et al. 2004). While we have listed radially and vertically average ‘disc’ properties for these unstable cases in Table 1, we do not include these systems in relevant figures below. In order to present results for a large, stable, pure gas disc, we use the $V_{\text{max}} = 168 \text{ km s}^{-1}$ simulation from Kaufmann et al. (2007) with $T_F = 3 \times 10^4 \text{ K}$. This system had a slightly larger spin parameter than the rest of our runs ($\lambda_g = 0.038$).

We note that our final galaxies have larger maximum circular velocity scales than their initial haloes because of the effects of baryonic contraction (compare the second and last columns in Table 1). For example, our D41 series produce galaxies that are comparable in rotation speed to dwarf irregular galaxies (dIs) like the Large Magellanic Cloud at $\sim 60 \text{ km s}^{-1}$. Our smallest (D24) runs produce galaxies that are large enough ($\sim 35 \text{ km s}^{-1}$) to be included in the Geha et al. (2006) sample of SDSS dwarfs. Our larger galaxies, G74 and G148, produce systems that are comparable to M33 ($\sim 100 \text{ km s}^{-1}$) and the Milky Way ($\sim 200 \text{ km s}^{-1}$).

Finally, we address our initial conditions in light of the idea of ‘cold flows’ put forward by Kereš et al. (2005) and Birnboim & Dekel (2003). These authors find that gas is not shock-heated to the virial temperature in small haloes, $M_c \lesssim 10^{11} \odot$, but rather is accreted as ‘cold’ material, with $T_F \lesssim 10^4 \text{ K}$. Our models are not strongly at odds with this picture. Specifically, the gas within our small haloes cools very quickly to the temperature floor and indeed falls into the central region in its ‘cold’ phase.

### 3.2 Results 1: morphological trends

The upper and lower panels of Fig. 2 illustrate the final projected stellar density for the D24 and D53 runs. It is evident that even the mild temperature floor, $T_F = 1.5 \times 10^4 \text{ K}$, has resulted in a very thick disc for the small, $\sim 35 \text{ km s}^{-1}$ galaxy, while the larger system, $\sim 85 \text{ km s}^{-1}$, is closer to a standard thin disc.

We note that both of the systems in Fig. 2 have formed substantial central bulge components. These central stellar mass concentrations are likely an artefact of our simple initial conditions, which assume a centrally concentrated NFW profile for the hot gas. We return to this potential shortcoming in Section 4.

In order to provide a more quantitative comparison between runs, we have estimated a disc scalelength, $R_d$, and scaleheight $z_d$, for each galaxy. We have explored several methods for quantifying $R_d$ and $z_d$ and find that our overall results change very little between methods. Because of the large bulge component, our galaxies are not well described by a single exponential surface density profile. The radial scale length, $R_d$, is therefore found by fitting an exponential profile to the outer part of the projected, face-on surface density profile, neglecting the bulge region. The vertical scaleheight, $z_d$, is determined by fitting an exponential profile to the projected, edge-on surface density profile at a projected radius equal to $R_d$ (this avoids the bulge region). The fit is typically good out to vertical scales as large as $\sim 3z_d$ above the disc. The measured values for each simulation are listed in Table 1.

Fig. 3 presents the galaxy ‘thickness’ ratio ($R_d/z_d$) as a function of the (edge-on) gas rotational velocity, $V_{22}$, measured at $2.2 R_d$ for each disc. Symbol types correspond to different temperature floors as indicated. Discs are thicker in smaller haloes and for larger temperature floors. The arrows indicate that the stars in the largest galaxies have been artificially thickened by numerical heating.

**Figure 2.** Edge-on views of a simulated dwarf galaxy (D24, upper panel) and a more massive galaxy (D53, lower panel). The grey-scale maps the projected stellar density. The disc of the larger galaxy is clearly thinner than the disc of the dwarf. The vertical bars indicate twice the softening length used in the simulations.

**Figure 3.** Galaxy disc ‘thinness’ as a function of the circular velocity for our star formation runs. Here $V_{22}$ is the rotational velocity of the gas measured at $2.2 R_d$ for each disc. Symbol types correspond to different temperature floors as indicated. Discs are thicker in smaller haloes and for larger temperature floors. The arrows indicate that the stars in the largest galaxies have been artificially thickened by numerical heating.
Therefore, the general trend with decreasing thickness, seen between \( \sim 40 \) and 100 km s\(^{-1}\) should be robust.

Fig. 4 shows that the same morphological trend is seen in our pure gas runs without star formation. We do not plot the massive G74\(_g\) and G143\(_g\) galaxies. As mentioned above, the gas became so cold in these runs \((T_g = 1.5 \times 10^4\) K\) that the final discs fragmented into thin, clumpy, irregular systems. The open hexagon at \(V_{2,2} = 213\) km s\(^{-1}\) is simulation G168\(_g\)HRLS, where HRLS refers to the Milky Way model described in Kaufmann et al. (2007). This system is hot enough to be stable, with \(T_g = 3 \times 10^4\) K, and ends up as a very thin disc. Overall, the agreement between our pure gas runs and those with star formation suggests that the correlation between disc thinness and circular velocity should hold, and is largely independent of uncertainties associated with star formation.

### 3.3 Results 2: gas fractions and star formation

In the previous section, we showed that galaxies formed within small haloes tend to be thicker than those formed within large haloes. Fig. 5 shows that the SFE in our simulated galaxies also varies as a function of \(V_{2,2}\). We define SFE = \(m_\ast/m_g\), where \(m_\ast\) is the star formation rate and \(m_g\) is the gas associated with the galaxy. Specifically, \(m_g\) is defined to be the mass of gas that is both cold \((T = T_g)\) and no longer infalling. It is evident from Fig. 5 that our dwarf galaxies are less efficient in turning gas into stars than are larger galaxies, as expected. Moreover, at a fixed circular velocity, the efficiency is reduced for higher ISM temperatures.

Another observationally oriented measure of the efficiency of star formation is the cool gas fraction, \(m_g/(m_g + m_\ast)\). The upper and lower panels of Fig. 6 show the evolution of the cool gas with time in our galaxies. We find that the cool gas fraction approaches a constant after \(\sim 3\) Gyr. This corresponds to the time when the infall of new cool gas reaches an equilibrium with the rate gas is being converted into stars in the galaxy. The upper panel shows the evolution for galaxies with different (final) circular velocities \((V_{2,2})\) at a fixed ISM temperature \(T_g = 1.5 \times 10^4\) K. The lower panel shows our D53 series for three values of \(T_g\). Larger systems end up with lower gas fractions, as do systems with decreasing ISM temperatures. Fig. 7 shows the same data sliced at a fixed time (3 Gyr) plotted as a function of \(V_{2,2}\). Clearly, the gas fractions are higher in smaller galaxies, as expected.

### 4 DISCUSSION

Geha et al. (2006) looked at a sample of 101 extremely low luminosity dwarf galaxies selected from the Sloan Digital Sky Survey, and found a trend for dwarfs to be systematically much more gas rich than giants (e.g. Geha et al. 2006, fig. 3). The results presented in the previous section (Fig. 7) show encouraging agreement with the observed trend. However, Geha et al. find an average gas fraction in dwarfs of \(\sim 0.6\), and our simulated dwarfs have gas fractions that are lower, \(\sim 0.3\). The comparison may be even worse than it appears because the observations constrain only the neutral H\(\text{I}\) fraction. At \(T \sim 10^4\) K, however, the difference between the neutral and total fractions is expected to be small. While we regard the predicted trend between the gas fraction and velocity scale as the most robust aspect of this work, it is worth investigating whether simple adjustments might bring our results into closer agreement with the data.

An obvious problem with our simulations is that our galaxies all end up with lower gas fractions, as do systems with decreasing ISM temperatures. Fig. 7 shows the same data sliced at a fixed time (3 Gyr) plotted as a function of \(V_{2,2}\). Clearly, the gas fractions are higher in smaller galaxies, as expected.

4 Note, however, that these observations possibly underestimate the stellar masses because contributions from extended, low surface brightness stellar populations are likely to be missed (M. Blanton, private communication; or see Roberts & Haynes 1994; van Zee 2001).
nuclear structures in our galaxies. As seen by the stars, hexagons, and open diamond in Fig. 8, these ‘disc’ gas fractions are more in line with observations.

Of course, another clear uncertainty in any galaxy formation simulation is star formation. The most-important parameter in our prescription is the density threshold for star formation, $\rho_{SF}$. Observationally, we can constrain only the relationship between the projected gas density and star formation rate (Kennicutt 1998); however, because the density threshold in our prescription is three dimensional, we are left with the freedom to explore its parameter space.\footnote{We refer the reader to Kravtsov (2003) for an interesting theoretical discussion on the origin of the Schmidt–Kennicutt relation.} The squares with the crosses in Fig. 8 show the result of two runs (D24,d and G148,d) with $\rho_{SF}$ set at 100 times our fiducial value (to $2.5 \times 10^{6} \, \text{M}_\odot \, \text{kpc}^{-3}$). Note that in order to more directly compare with the fiducial runs, we have not excluded bulge stars in these points. As might be expected, the increased threshold produced a much higher gas fraction for the dwarf galaxy compared to the standard case (Fig. 7). It also produced a smaller disc than the fiducial run, but a similar axial ratio. Unlike the small galaxy, the gas fraction in the G148,d system is quite similar to that in the fiducial run (Fig. 7) because the gas was able to become quite dense and form stars. Like the fiducial Milky Way–size galaxy, this system also sits on the Kennicutt relation. We note, however, that unlike the fiducial case, G148,d produced $\sim 10$ very dense star clusters in the final disc. Numerical scattering off these clusters dramatically affected
the star particle orbits, and artificially increased the scaleheight of the final disc.

Elmegreen & Parravano (1994), Blitz & Rosolowsky (2004, 2006) and Wong & Blitz (2002) pointed out the relation between the gas pressure in the mid-plane of the galaxy and the ratio of H$_2$ versus H$_1$, and related also the SFE. The gas pressure in the mid-plane $P/k_B$ in our simulations has values ranging from $4 \times 10^4$ to $8 \times 10^4$ cm$^{-3}$ K in agreement with the findings of Blitz & Rosolowsky (2006), but does not show a strong evolution with galaxy mass. In the simulations, the pressure stabilizes the gas well above the mid-plane for the dwarfs, but not for the more massive galaxies, making the mid-plane pressure less meaningful for the dwarf galaxies.

While it is not the aim of this paper to reproduce the observations in detail, we conclude that there are several physically plausible effects that can eventually lead to a more complete understanding of the gas fractions in small systems. Overall, the agreement between the predicted and observed trends is quite encouraging.

5 SUMMARY AND CONCLUSIONS

We have used SPH simulations and an analytic discussion to argue that many of the observed changes in galaxy properties as a function of their rotation speed arise naturally because of the increased pressure support radius in dwarf galaxies, $\sim 40$ km s$^{-1}$. This suggests that most small galaxies are not formed as thin discs, but rather are born as thick, puffy systems.

(ii) For a constant temperature floor, pressure support becomes less important in large haloes, and this naturally produces a tendency for massive, isolated galaxies to have thicker discs than their less-massive counterparts, as observed.

(iii) The morphological trend produces related trends in the SFE: dwarf galaxies are predicted to have longer star formation timescales than larger galaxies. Similarly, galaxy gas fractions decrease with the circular velocity, as observed.

The expected morphological trend seems to be fairly independent of star formation details (cf. Figs 3 and 4). While relations of this kind are difficult to quantify observationally for a large number of galaxies, Yoachim & Dalcanton (2006) used a sample of 34 late-type, edge-on, undisturbed disc galaxies to show that more massive galaxies are generally thinner than less-massive galaxies (see their fig. 5). They find radial-to-vertical axial ratios for dwarf galaxies as low as $\sim 3$, in agreement with results presented in our Fig. 3.

More clues to the nature of galaxy formation on small scales can be gained from the population of dSphs. Unlike equally-faint dls, dSphs are gas-poor. The fact that gas-poor dwarfs are exclusively found in the proximity of a luminous neighbour (Geha et al. 2006) encourages the notion that tidal forces and ram pressure stripping act to transform dI-type galaxies into dSphs (Gunn & Gott 1972; Lin & Faber 1983; Moore & Davis 1994; Mayer et al. 2001a,b, 2002, 2006, 2007; Mastropietro et al. 2005). Typically, models aimed at testing this transformation hypothesis initialize a thin disc within a small dark matter halo and investigate how tides or ram-pressure affect the galaxy as it falls into a larger host.

Mayer et al. (2006) and Mayer et al. (2007) used SPH simulations to show that the combined effects of tides and ram pressure can convert discy dwarfs to gas-poor spheroidal systems, but only if a heating source is imposed to keep the gas in the dwarf extended and hot at a temperature of $\sim 2.5 \times 10^4$ K (L. Mayer, private communication). As we have shown, temperature floors of this magnitude inhibit the formation of thin discy dwarfs in the field. If a puffy dwarf of the kind we expect falls into the potential well of a larger galaxy with an extended hot gas halo, it should be quite susceptible to gas loss and morphological transformation. Trends of this kind do seem to be broadly in accord with some observations (e.g. Lisker et al. 2007; Geha et al. 2006). In another investigation, Mastropietro et al. (2005) used N-body simulations to study the transformation of discy dwarfs to spheroidal dwarfs. They had some success, but were unable to reproduce the observed fraction of spheroidal dwarfs with negligible rotational support. Our results suggest that field dwarfs are likely to be born thicker than typically assumed and are therefore more susceptible to kinematic transformations.

It has long been recognized that galaxy formation must become increasingly inefficient in dark matter haloes from the scale of big spirals to small dwarfs (White & Rees 1978; Klypin et al. 1999; Moore et al. 1999; Strigari et al. 2007). Our work suggests that it is difficult to avoid the suppression of galaxy formation efficiency in small haloes. Shallow potential wells naturally give rise to puffy galaxies with long star formation time-scales. This situation makes them more susceptible to other feedback effects and external influences that may act to suppress star formation even further. Small galaxies are also systematically more metal-poor than larger systems (e.g. Tremonti et al. 2004). The lower efficiency of star formation may also explain the observed mass–metallicity relation without the need for strong winds (Tassis et al. 2006). For example, Brooks et al. (2007) recovered in their cosmological simulations the observed relation only by including an allowance for ISM heating (see also Ricotti & Gnedin 2005).

A natural extension of this work would be a more detailed modelling of the coupling between various energy sources and the ISM. Ideally, this would include a star formation prescription based on molecular cooling and radiative transfer for the treatment of the feedback from stars to the ISM – allowing to overcome the simple proxy of a temperature floor.

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REFERENCES

Balsara D. S., 1995, Journal of Computational Physics, 121, 357
Barnes J., Efstathiou G., 1987, ApJ, 319, 575
Bate M. R., Burkert A., 1997, MNRAS, 288, 1060
Benson A. J., Lacey C. G., Baugh C. M., Cole S., Frenk C. S., 2002, MNRAS, 333, 156
Birnboim Y., Dekel A., 2003, MNRAS, 345, 349

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