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DARK SATELLITES AND THE MORPHOLOGY OF DWARF GALAXIES

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ABSTRACT

One of the strongest predictions of the ΛCDM cosmological model is the presence of dark satellites orbiting all types of galaxies. We focus here on the dynamical effects of such satellites on disky dwarf galaxies, and demonstrate that these encounters can be dramatic. Although mergers with $M_{\rm sat} > M_d$ are not very common, because of the lower baryonic content they occur much more frequently on the dwarf scale than for L_*-galaxies. As an example, we present a numerical simulation of a 20% (virial) mass ratio merger between a dark satellite and a disky dwarf (akin to the Fornax dwarf galaxy in luminosity) that shows that the merger remnant has a spheroidal morphology. We conclude that perturbations by dark satellites provide a plausible path for the formation of dSph systems and also could trigger starbursts in gas rich dwarf galaxies. Therefore the transition from disky to the often amorphous, irregular, or spheroidal morphologies of dwarfs could be a natural consequence of the dynamical heating of hitherto unobservable dark satellites.

Subject headings: galaxies: dwarf, interactions, evolution; (cosmology:) dark matter

1. INTRODUCTION

According to the ΛCDM scenario, stellar disks are immersed in dark matter halos and are surrounded by a full spectrum of satellite companions. Encounters with these satellites can inject significant amounts of energy into the system, with consequences that vary from negligible to fully catastrophic disk destruction depending on the relative mass of the perturber and the configuration of the event (relative distances and velocities). Disk heating by such substructures has been addressed in previous work (Toth & Ostriker 1992; Quinn et al. 1993; Font et al. 2001; Benson et al. 2004), but has generally focused on the effect on bright Milky Way-like galaxies.

Cold dark matter models predict the structure of halos to be self-similar; in such a way that, when properly scaled, a Milky Way-sized halo looks comparable to one hosting a faint dwarf galaxy (Moore et al. 1999; Springel et al. 2008; Klimentowski et al. 2010; Wang et al. 2012). However, galaxy formation is not a self-similar process, as the properties of galaxies depend in a complex way on e.g. the mass of their host halos. For example, low mass (dwarf) galaxies are much more inefficient at forming stars (Blanton et al. 2001; Robertson & Kravtsov 2008) and have much higher mass-to-light ratios than larger galaxies (Yang et al. 2003; Walker et al. 2009). In addition, gas cooling is likely to be (nearly) completely inhibited in dark matter halos with masses below $\sim 10^8 h^{-1}\,{\rm M}_\odot$ (Kaufmann et al. 2007), which implies that the satellites of dwarfs should be generally completely dark in contrast to satellites in galaxy clusters or around L_*-galaxies.

In this *Letter* we show that these considerations imply that the dynamical perturbations of dark-matter satellites on dwarf galaxies are much more important than on L_*-galaxies. Dark satellites may provide a channel for the formation of dwarf spheroidal galaxies without the need to recur to environmental effects (Mayer 2010) or multiple body interactions (Sales et al. 2007). Such interactions may also be responsible for the observed increase of disk "thickness" towards fainter galaxies (Yoachim & Dalcanton 2006), as well as explain the existence of isolated dwarfs undergoing intense starbursts without an apparent trigger (Bergvall 2011) as a result of a major merger with a dark companion (T. K. Starkenburg et al., in prep.).

2. MODELS

Our goal is to quantify the effects of substructures on disk-like galaxies over a broader region of parameter space (and specifically mass range) than done in previous work. To this end, we use the second resolution level of the *Aquarius Simulations* (Springel et al. 2008) and study the assembly history of *main* (as opposed to satellite) dark matter halos in the mass range $10^8 - 10^{12} h^{-1} M_\odot$. We follow their evolution from $t = 2$ Gyr onwards ($z \leq 3$), since by this time all halos in our sample have accreted at least 10% of their final mass, and the concept of "main/host" is well-defined. At the present time, we find 739 such halos, including the six main *Aquarius* Milky Way-like objects. We have identified substructures in these halos with the SUBFIND algorithm (Springel et al. 2001) and tracked their orbits by following the position of their most-bound particle.

We populate these dark matter halos with "galaxies" following a semi-analytic model that uses simple but physically motivated laws to track the evolution of gas cooling, star formation and feedback processes (Li et al. 2010; Starkenburg et al. 2012). This allows us to derive their baryonic properties such as their gas content, stellar mass, etc. Our model simultaneously reproduces the luminosity function, scaling relations and chemical content of bright as well as dwarf galaxies (for a more detailed description see Starkenburg et al. 2012).

When a disk galaxy accretes a low mass companion, it is (vertically) heated and puffed up. The increase in the scale height ΔH for a disk of (total, i.e. stellar and gas) mass M_d and scale length R_d caused by an interaction with a satellite of mass $M_{\rm sat}$ may be estimated using analytic arguments to be

$$\frac{\Delta H}{R_d} = \alpha(1 - f_{\rm gas})\,\frac{M_{\rm sat}}{M_d}, \qquad (1)$$

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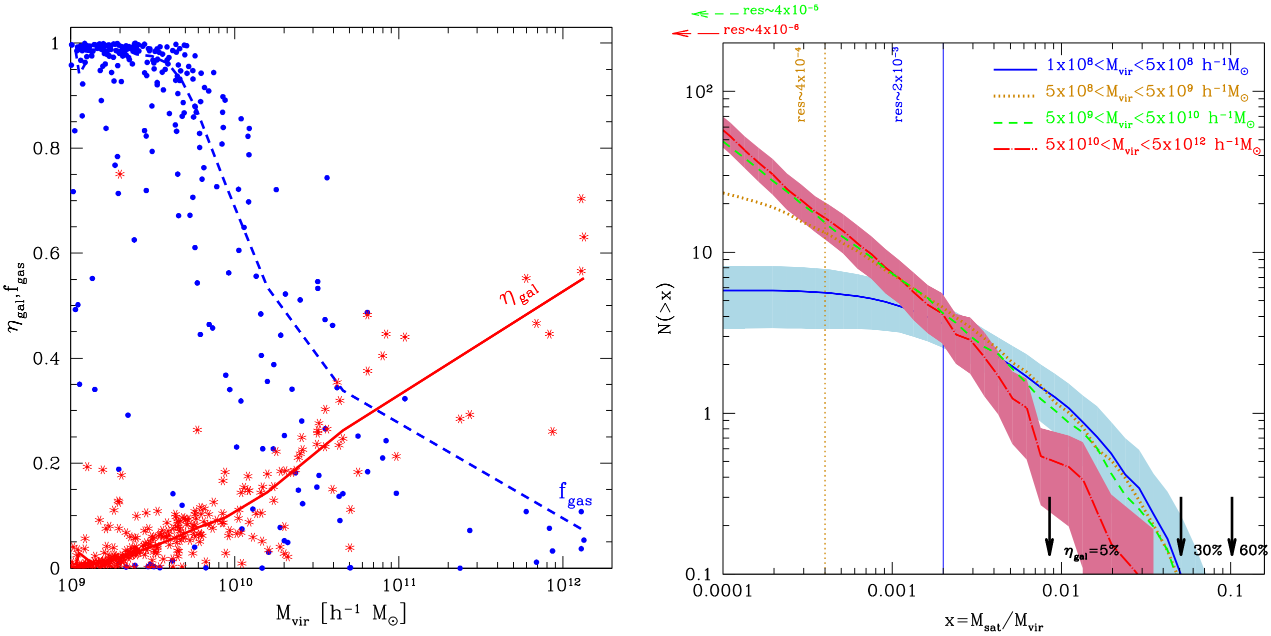

FIG. 1.— *Left:* Gas fraction $f_{\rm gas}$ (blue circles) and galaxy formation efficiency $\eta_{\rm gal}$ (red asterisks) as a function of host mass as predicted by our SA model. The dashed blue and solid red curves indicate the respective median trends. *Right:* The "Spectrum of perturbers" $N(>x)$ gives the number of encounters with objects of a given mass ratio $x = M_{\rm sat}/M_{\rm vir}$ (see text for more details). The shaded regions correspond to the 25 and 75 percentiles and were derived from 100 random subsamples with each 5 host halos belonging to a given mass range (and are shown for clarity only for the two mass ranges). The black arrows indicate $M_d/M_{\rm vir}$ for three representative values of $\eta_{\rm gal} = 5, 30$ and 60%, while the thin vertical lines are the SUBFIND mass resolution.

(Toth & Ostriker 1992; Mo et al. 2010). Here $f_{\rm gas} = M_{\rm gas}/M_d$ is the gas fraction of the host disk and its inclusion in Eq. (1) accounts for the energy that is radiated away and not transferred into random motions of disk stars (e.g. Hopkins et al. 2008). We have carried out a series of merger experiments on the scale of dwarfs (and used analogous simulations of large disks by Velazquez & White 1999; Villalobos & Helmi 2008; Purcell et al. 2009; Moster et al. 2010), and confirm the above dependence on the ratio $M_{\rm sat}/M_d$. We have found the proportionality constant to be $\alpha \sim 0.03$ when the above expression is evaluated at $R = 2.5R_d$. Below we present two examples of such merger simulations and report our results in more detail in T. K. Starkenburg et al., in prep.

Eq. (1) can be re-written in terms of the "disk galaxy efficiency" of a given halo: $\eta_{\rm gal} = M_d/(M_{\rm vir} \times f_{\rm bar})$, i.e. the fraction of baryons collected in the central galaxy compared to the total available budget. Here $M_{\rm vir}$ is the virial mass of the host halo and $f_{\rm bar} \sim 0.17$ is the universal baryon fraction. Therefore

$$\frac{\Delta H}{R_d} = \frac{\alpha}{f_{\rm bar}} \frac{(1 - f_{\rm gas})}{\eta_{\rm gal}} \frac{M_{\rm sat}}{M_{\rm vir}}. \qquad (2)$$

Thus three quantities affect the efficiency of disk heating: the gas fraction $f_{\rm gas}$, the galaxy efficiency $\eta_{\rm gal}$ and the mass of the perturber compared to that of the host $M_{\rm sat}/M_{\rm vir}$. We now investigate each of these factors using our models.

The blue solid circles in the left panel of Fig. 1 show $f_{\rm gas}$ as a function of host halo mass in the SA model. Note that the gas content of a galaxy depends strongly on the mass of its halo: for objects less massive than $10^{10}h^{-1}M_\odot$ more than 90% of the baryonic mass assembled onto the central galaxy remains as cold gas, revealing how inefficient star formation is in (isolated) dwarf galaxies. On the other hand, Milky Way-sized objects have typically $\sim 10 - 20\%$ of their baryons in gas; all these numbers being in reasonably good agreement with observations (McGaugh et al. 2010).

The red asterisks in the left panel of Fig. 1 show $\eta_{\rm gal}$ as function of halo mass. As indicated by the median trend (red solid line), halos become increasingly inefficient in collecting baryons onto galaxies as they become less massive: for $M_{\rm vir} < 10^{10}h^{-1}M_\odot$, $\eta_{\rm gal} \sim 1 - 10\%$. This is the result of a combination of the effect of a UV ionizing background and of supernova feedback (Li et al. 2010; Macciò et al. 2010; Okamoto et al. 2010). These processes need to be taken into account to match the satellite luminosity function (Guo et al. 2010; Moster et al. 2010), and explain why dwarf galaxies are the most dark matter dominated objects known in the Universe.

The right panel of Fig. 1 shows the cumulative subhalo mass function for our sample of main halos in the *Aquarius* simulations for four different ranges of host mass. Since disk heating is expected to be more efficient for perturbers that adventure close to the center of the host halo, we measure the subhalo mass at the first pericenter that is within a distance smaller than 30% of the virial radius of the host and normalize it to the virial mass of the host at that time. The thin vertical lines indicate the subhalo resolution, defined by the 20-particle threshold imposed by the SUBFIND algorithm[6]. Within the range that is well resolved (to the right of the vertical lines), we find that the mass spectra of satellites at pericenter are all comparable and independent of the virial mass of the host.

Because the efficiency of galaxy formation $\eta_{\rm gal}$ depends strongly on $M_{\rm vir}$ (see left panel of Fig. 1), at fixed gas content the heating produced by satellites is expected to be significantly larger for small mass hosts (halos with $M_{\rm vir} < 10^{10}h^{-1}M_\odot$) than for Milky Way-like galaxies. To first order this is hinted

[6] Note that for the least massive host halos we are able to resolve fewer substructures than for Milky Way-like hosts, and that the SUBFIND algorithm is known to underestimate the mass at pericenter, hence the above values are lower limits.

by the vertical arrows in the right panel of Fig. 1. These arrows show the mass ratio $M_d/M_{\rm vir}$ for three different values of galaxy efficiency: $\eta_{\rm gal} = 5, 30$ and 60%, and can be used as a guide to determine the number of encounters with satellites with $M_{\rm sat} \sim M_d$ for a system with a given efficiency. It then becomes clear that such encounters are much more common for dwarf galaxies, which have lower $\eta_{\rm gal}$. For example, a dwarf galaxy ($\eta_{\rm gal} \sim 5\%$), experienced on average 1.5 encounters with an object of comparable mass in the last 11.7 Gyr. On the other hand, for a Milky Way-like galaxy whose disk mass is $\sim 10\%$ of the virial value ($\sim 5\%$ for $\eta_{\rm gal} = 30\%$), the number of encounters with a significant perturber are a factor ~ 15 less common. Note that these estimates are somewhat lower than derived in previous work for $\sim 10^{12}\,{\rm M}_\odot$ hosts (Purcell et al. 2009) and this could be due to the environment of the *Aquarius* halos.

3. RESULTS

Fig. 2 shows, for our model galaxies, $\Delta H/R_d$ as function of host halo mass, normalized to the values expected for a galaxy like the Milky Way (with $\eta_{\rm gal} = 0.45$ and $f_{\rm gas} = 0.1$) and for fixed $M_{\rm sat}/M_{\rm vir}$. The red curve indicates the expected change *when the gas fraction is that of the Milky Way*. This shows that for a dwarf galaxy populating a $10^9 h^{-1} M_\odot$ halo, the heating of a disk is expected to be ~ 100 times larger than for a galaxy like the Milky Way embedded in a $10^{12} h^{-1} M_\odot$ halo. For example, even an encounter with a low mass perturber ($M_{\rm sat}/M_{\rm vir} = 0.05$) would be devastating and turn a disky dwarf galaxy into a dwarf spheroidal since $\Delta H/R_d \sim 2.7$ for $M_{\rm vir} = 10^9 h^{-1} M_\odot$ and $f_{\rm gas} = 0.1$ according to Eq. (2). On the other hand, the effect of such an encounter would be nearly negligible in the case of a Milky-Way like galaxy.

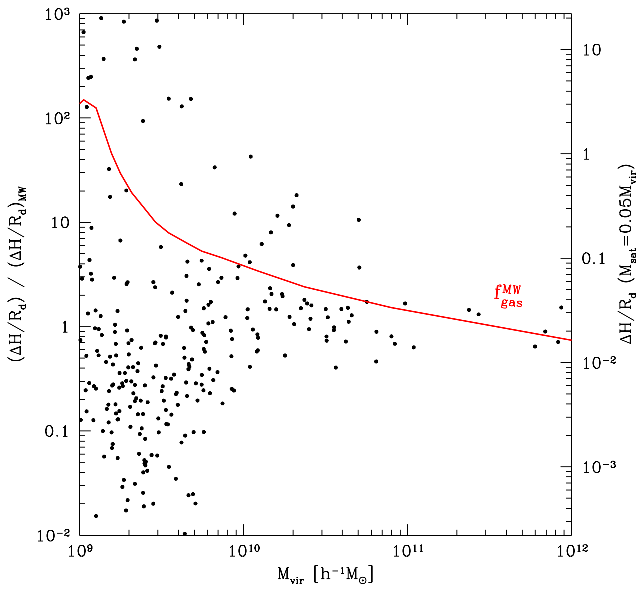

FIG. 2.— Relative increase in the disk's thickness $\Delta H/R_d$ as a function of the virial mass of the host computed using Eq. (2) for all the main galaxies in the Aquarius simulations (black dots). The red curve shows the median expected change for $f_{\rm gas} = 0.1$. All values have been normalized to the heating expected for an L_* galaxy, with $f_{\rm gas} = 0.1$ and $\eta_{\rm gal} = 0.45$. The scale on the right vertical axis indicates the absolute change in $\Delta H/R_d$ assuming an encounter with a $M_{\rm sat} = 0.05 M_{\rm vir}$ perturber.

On the scale of Milky Way galaxies the heating is dominated by subhalos hosting stars, while around smaller hosts ($M_{\rm vir} < 10^{10} h^{-1} M_\odot$) the subhalos will generally be *dark* as they fall below the mass threshold imposed by reionization and efficient atomic hydrogen cooling to form stars. To confirm that such dark satellites leave imprints on the morphologies of dwarf galaxies, we have performed a set of numerical experiments. We focus here on two simulations where we varied the mass ratio between the disk and the satellite, but took $M_{\rm sat}/M_{\rm vir} = 0.2$ comparable to what has been used in previous work (Kazantzidis et al. 2008; Villalobos & Helmi 2008; Purcell et al. 2009; Moster et al. 2010). The satellite follows an NFW profile with concentration $c = 18.7$ (Muñoz-Cuartas et al. 2011). Our disk galaxies are purely stellar, they have $M_d = 0.008$ and $0.04 \times M_{\rm vir}$, and are embedded in a Hernquist halo with mass $M_{\rm vir} = 10^{10} h^{-1}\,{\rm M}_\odot$, and scale-radius $a = 9.3$ kpc, i.e. $\eta_{\rm gal} \sim 5\%$ and 23% respectively. The disks are radially exponential with scale-length $R_d = 0.67 h^{-1}$ kpc, and vertically they follow ${\rm sech}^2(z/2z_0)$, with $z_0 = 0.05 R_d$. The internal kinematics are set-up following Hernquist (1993), and the disks are stable (with Toomre parameters $Q > 1$).

We put the satellite on a fairly radial orbit with $r_{\rm apo}/r_{\rm peri} = 40$, starting from a distance of ~ 23 kpc, and found that it is completely disrupted after three close passages, i.e. in ~ 1.5 Gyr. Fig. 3 shows the final surface brightness profiles of the heavy and light disks in the top and bottom panels respectively. This figure evidences that significant heating has taken place and even led to important changes in the morphology of the host galaxy. This is expected since although we simulated minor mergers in terms of virial mass ratios, these are major mergers from the perspective of the dwarf galaxy, as $M_{\rm sat}/M_d = 5$ and 25 respectively.

In the case of gas-rich systems –which are a majority at the low mass end, encounters with dark satellites will be less efficient at changing the structure of the host dwarf galaxy, because much of the orbital energy will be absorbed by the gas, leading to less vertical heating. However, we may expect that such encounters may induce star formation events, and thus, albeit indirectly, lead to significant changes in the characteristics of these galaxies (T. K. Starkenburg et al., in prep).

To establish whether observations support that disks of dwarf galaxies are thicker than those of larger systems, we have compiled measurements of the thickness of *stellar* disks (quantified by the apparent axis ratio, b/a) for a wide range of galaxy masses. Although the observed b/a is not a measurement of the intrinsic shape of the disk, if one assumes random orientations on the sky, the two are directly related. In our literature search we have carefully selected *isolated late-type* galaxies to avoid any morphology-luminosity trend that may be driven by environmental interactions (such as discussed in Mayer 2010).

The top panel of Figure 4 shows the distribution of optical (r or R band) b/a as a function of circular velocity ($V_c = W_{50}/2$). The latter provides a measure of the dynamical mass of the galaxy and its dark matter halo. We plot here data for two galaxy samples: HOPCAT (black dots; Doyle et al. 2005) containing the optical counterparts of ~ 3600 HIPASS sources, and for a set of isolated nearby late type galaxies (blue asterisks; Karachentsev et al. 2004, tidal index $\Theta < 0$, RC3 morphological type > 0). The magenta square shows the median value for a subsample of the 101 dwarf galaxies (Geha et al. 2006), where we have selected only those objects with no companions within 1 Mpc projected distance and $(g - r) < 0.55$. The bot-

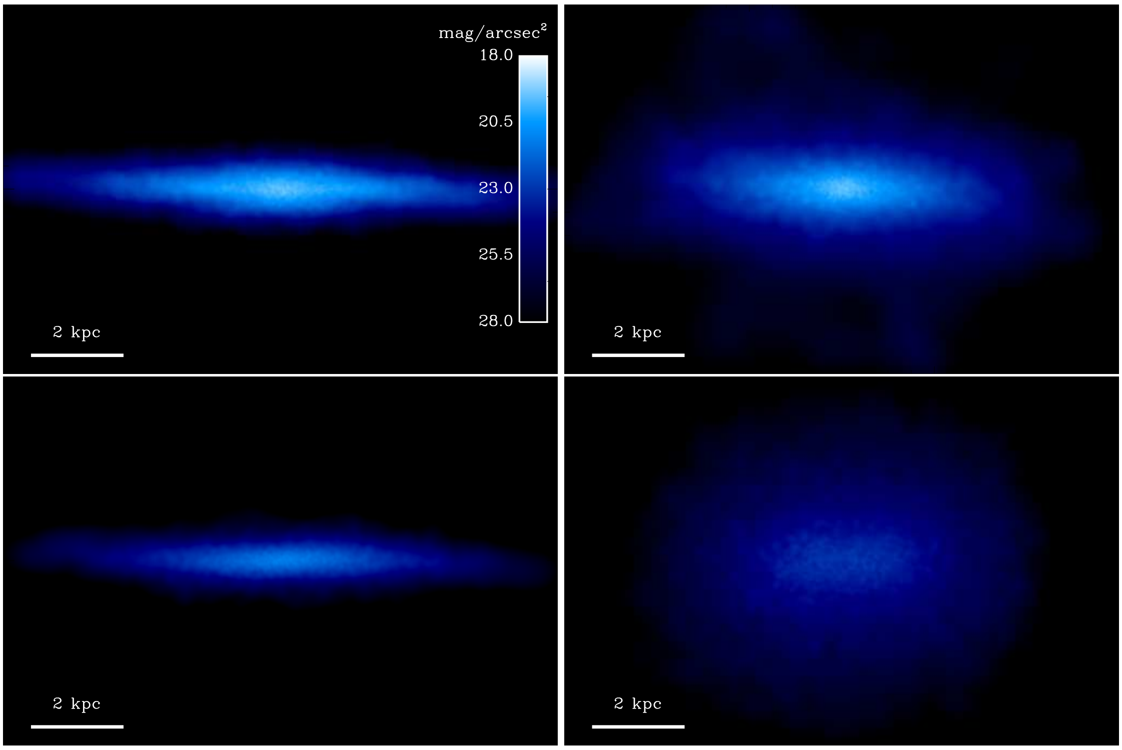

FIG. 3.— The left panels show the initial surface brightness profiles for two of our simulated dwarf galaxies with $M_d/M_{\rm vir} = 0.008$ and 0.04 (bottom and top panels, respectively). The panels on the right correspond to the final stellar distributions after these disks merged with a dark satellite of mass $M_{\rm sat} = 0.2M_{\rm vir}$, and are shown after 6 Gyr of evolution (i.e well after the merger has taken place, so the system appears to be relaxed again).

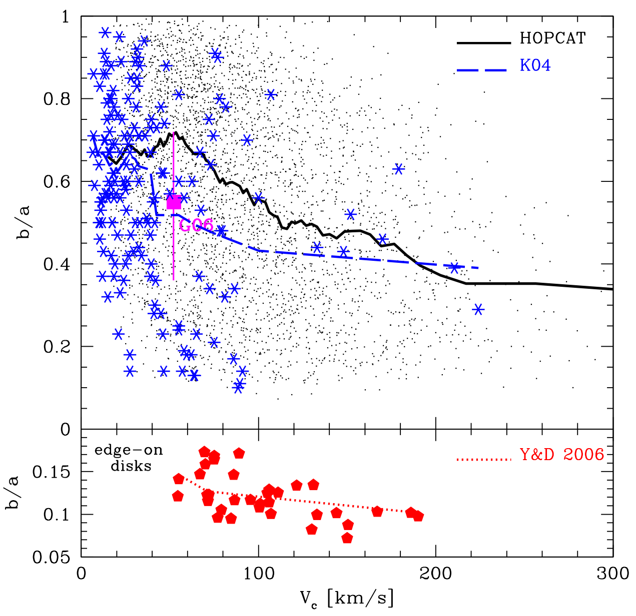

FIG. 4.— Apparent optical axis ratios b/a for various samples of isolated, late-type galaxies from the literature. *Top panel*: HOPCAT (Doyle et al. 2005; black dots), a sample of nearby galaxies selected from Karachentsev et al. (2004; blue asterisks) and the median of the sample of dwarf galaxies presented by Geha et al. (2006; magenta square with vertical bar showing the 25-75% percentiles). *Bottom panel:* Edge-on galaxies from Yoachim & Dalcanton (2006). These are shown separately because the b/a corresponds to their true axis ratio, i.e. z_0/R_d. The lines indicate, for each sample, the median b/a at a given circular velocity V_c.

tom panel of this Figure shows the intrinsic thickness defined as the ratio of scale-height to scale-length for a sample of edge-on disks (Yoachim & Dalcanton 2006).

The median b/a trends with galaxy circular velocity are indicated separately for each sample by the black solid (HOPCAT), blue dashed (Karachentsev et al. 2004) and red dotted (Yoachim & Dalcanton 2006) curves. Each set clearly shows that the axis ratios increase with decreasing circular velocities. In other words, stellar disks become thicker as we move towards less massive galaxies, in qualitative agreement with our expectations based on the analysis of disk heating by substructure on isolated galaxies (see also Sanchez-Janssen et al. 2010).

4. DISCUSSION

We have demonstrated that the dynamical effects of dark satellites on disky dwarf galaxies are much more dramatic than on galaxies like the Milky Way. Mergers with $M_{\rm sat} > M_d$ are not very common for $z < 3$ but they occur much more frequently than on the L_*-galaxies scale. As an example, we have simulated a merger with $M_{\rm sat}/M_{\rm vir} = 0.2$ for a dwarf with $M_d = 8 \times 10^7 h^{-1}\,{\rm M}_\odot$ in stars, i.e. slightly more massive than the Fornax dwarf galaxy, and found that its morphology changed from disky to spheroidal. This might be a plausible path for the formation of dSph systems in isolation (if the dwarf was gas poor, which is rare in our models but not unlikely). This channel might also be relevant for the dSph satellites of our Galaxy, provided such encounters would have taken place just before the system fell onto the potential well of the Milky Way (since further gas accretion would thus be prevented).

Most of the galaxies on the scales of dwarfs are, however, gas-rich. In that case, encounters with dark satellites can trigger starbursts, which might explain the presence of seemingly isolated dwarfs undergoing major star formation events without an apparent trigger. Depending on the characteristics of the encounter, such starbursts will vary in amplitude. We are currently performing hydrodynamical simulations to characterize this process (T. K. Starkenburg et al. in prep).

Additionally, other processes exist that can influence the morphologies of dwarf galaxies. For example, binary mergers between disky dwarfs can result in the formation of spheroidal systems (Kazantzidis et al. 2011), although such events are rare (see Fig. 1). On the other hand, on the scale of dwarf galaxies physical processes affecting gas may also lead to thicker systems. For example, the presence of a temperature floor in the interstellar medium at $T \sim 10^4 K$ introduced by e.g. a UV background, implies that gas pressure becomes comparable to rotational support for small dark matter halos. Stars formed in such systems would thus be born in puffier configurations as demonstrated by Kaufmann et al. (2007) (see also, e.g. Robertson & Kravtsov 2008).

Yet, we have shown here that a distinctive imprint on dwarf galaxies will be left by dark satellites in the context of the ΛCDM cosmological paradigm. Such *dark satellites* are expected to make the stellar disks of isolated dwarf galaxies significantly thicker than those of $\sim L_*$ galaxies. We have indeed detected such a trend on three different observational samples of isolated late-type galaxies on the nearby Universe. We may have identified a new mechanism to explain the morphologies of dwarf galaxies.

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