Disc heating: possible link between weak bars and superthin galaxies

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ABSTRACT
The extreme flatness of stellar discs in superthin galaxies is puzzling and the apparent dearth of these objects in cosmological simulation poses challenging problem to the standard cold dark matter paradigm. Irrespective of mergers or accretion that a galaxy might be going through, stars are heated as they get older while they interact with the spirals and bars which are ubiquitous in disc galaxies – leading to a puffed up stellar disc. It remains unclear how superthin galaxies maintain their thinness through the cosmic evolution.

We follow the internal evolution of a sample of 16 initially extremely thin stellar discs using collisionless N-body simulation. All of these discs eventually form a bar in their central region. Depending on the initial condition, some of these stellar discs readily form strong bars while others grow weak bars over secular evolution time scale. We show that galaxies with strong bars heat the stars very efficiently, eventually making their stellar discs thicker. On the other hand, stars are heated very slowly by weak bars – as a result, galaxies hosting weak bars are able to maintain their thinness over several billion years, if left isolated. We suggest that some of the superthin galaxies might as well be forming weak bars and thereby prevent any strong vertical heating which in turn helps maintaining their thinness during the course of secular evolution.

Key words: galaxies:evolution – galaxies: haloes – galaxies: kinematics and dynamics – galaxies: structure – galaxies:spiral

1 INTRODUCTION
Galaxy formation under the ΛCDM cosmology produces too few thin, disc-dominated late-type galaxies with little or essentially no bulge (Mo et al. 1998; D'Onghia & Burkert 2001; Mayer et al. 2008). On the other hand, up-to-date observational surveys show abundance of flat galaxies (Karachentsev et al. 1999; Matthews & van Driel 2000; Kantsch et al. 2006) in the local universe. The apparent dearth of very thin disc galaxies in cosmological simulation has put up a challenge against the standard theory of CDM cosmology.

Superthin galaxies (hereafter SGs) are the extreme case of these flat edge-on galaxies with their axial ratios (defined as the ratio of scale height to the scale length) generally below 0.1. Due to the lack of strong morphological features SGs belong to the late-type in the Hubble classification scheme. In few cases, the thin discs of SGs are seen to be warped e.g., UGC 7170, UGC 3697 (in which case, the axial ratios are ~ 0.1) (Karachentsev et al. 1993) which could be considered as the limiting case of a superthin galaxy. SGs do have other unique properties of the late-type galaxies e.g., low surface brightness (LSB), high atomic hydrogen gas fractions, low metallicities (van der Hulst et al. 1993). The extreme thinness of the stellar discs suggest that SGs somehow prevent strong heating in the vertical direction. It is puzzling how SGs maintain their superthinness over several billion years since they are formed.

Observations point out that SGs, like many LSB galaxies, lack environmental influences (Rosenbaum et al. 2009; Galaz et al. 2011) which could give rise to tidal heating, heating due to satellite infall or mergers. The discs of superthin galaxies e.g., UGC 7321, IC2233 appear to be featureless, smooth with no visible signs of interactions such as tidal streams or other irregularities (Matthews et al. 1999; Matthews & Uson 2008). In contrast, the resulting stellar discs of CDM simulations are often smaller and thicker (Kazantzidis et al. 2008). This indicates that the heating of stellar discs of SGs are unlikely due to satellite infall, merger or due to massive subhalos (as it is in the CDM simulations). Since external mechanisms appear to be unimportant in heating stars of SGs, one must rely upon various internal sources. Indeed, as a galaxy evolves, internal heating of stars in the disc is unavoidable. In the case of our Milky...
Way, it is evident from the Hipparcos data (Binney et al. 2001). Recently, it has been shown by Saha et al. (2010) that a strong bar could efficiently heat stars in the vertical direction through physical processes like chaotic diffusion suggested by Pfenniger (1983). In fact, the possibility that superthin galaxies might be harbouring thin bars e.g., in UGC 7321 (Uson & Matthews 2003; Pohlen et al. 2003) could not be ruled out unambiguously. Bars are ubiquitous in disc galaxies (Eskridge et al. 2000; Barazza et al. 2008) suggesting that they are formed spontaneously and perhaps survive through the cosmic evolution (see Sellwood 2013, for a recent review). However, depending on the initial physical condition of a stellar disc and the distribution of dark matter, bars could grow to be stronger over a few rotation time scales or remain weak over several billion years (Saha et al. 2010). The analysis of Saha et al. (2010) further indicates that weak bars are not efficient in vertical heating of stars – implying that if an initially superthin galaxy were to prevent strong vertical heating, it could possibly do so by growing a weak bar at the most during the course of secular evolution.

The main focus of the current paper is to follow the evolution of such superthin galaxies embedded in various dark matter halo configuration and find out how many of these initial superthin galaxies are able to maintain their thinness such that they are still classified as superthin. We use collisionless N-body simulations to study the evolution of 16 initially superthin galaxies in isolation. Our study suggest that weak bars are perhaps the maximal non-axisymmetric features that a self-consistent superthin galaxy might be able to support in order to maintain their thinness over several Gyr.

The paper is organized in the following way. Section 2 describes the models of superthin galaxies and N-body simulation. Section 3 summarizes plausible sources of heating relevant for superthin galaxies. The detailed evolution of superthin galaxies is presented in section 4. Section 5 contains the discussion and primary conclusions from this work.

2 INITIAL GALAXY MODELS

The properties of stellar discs of superthin galaxies resemble many of the key properties of the late-type galaxies, especially that of the low surface brightness (LSB) galaxies (McGaugh et al. 1998; Matthews 2000). Like LSB galaxies, the dynamics in superthin galaxies are thought to be primarily governed by their surrounding dark matter halos. The dark matter dominance in LSB galaxies is evident from the decomposition of rotation curves (de Blok et al. 2001) and in the case of superthin galaxy UGC 7321 (Uson & Matthews 2003) from the combined modelling of the rotation curves and HI scale height (Banceree et al. 2011). The SGs are known to have poor star formation activities despite having higher neutral hydrogen gas fraction as in high surface brightness galaxies (van der Hulst et al. 1993; Boissier et al. 2003). The very low star formation rates and the apparent absence of strong two-armed spirals and/or strong bars suggest that the stellar discs in superthin galaxies are probably dynamically hot – indicative of a high value of Toomre’s stability parameter (Q) (see, Binney & Tremaine 1987). We utilize these general properties as guidelines to construct initial N-body models of extremely thin galaxies some of which are presumably progenitors of present day superthin galaxies.

We present here a sample of 16 very thin (with the ratio of scale height to scale length $h_z/R_d$ being less than 0.05 or close to it) equilibrium models of disc galaxies composed of a stellar disc, bulge and dark matter halo constructed using the method of Kuijken & Dubinski (1995). Each component in the galaxy model is live and interact with each other via gravitational forces. The models are scaled so that the unit of scale length ($R_d$) is 4 kpc and the circular velocity at about $2R_d$ is $\approx 200$ kms$^{-1}$. For relevant details on model construction, the readers are referred to Saha et al. (2010, 2012). The mass of the stellar disc and other physical parameters of each galaxy model are presented in Table 1. We primarily focus on two fiducial models namely, RHG116 and RHG102, and analyze their evolution in detail as a comparative study. Fig. 1 depicts the initial circular velocity curves for RHG116 and RHG102. Both the stellar discs of the two models have same initial thickness but the dark matter in the model RHG102 is dominating over the disc right from the center whereas dark matter contribution dominates in RHG116 only beyond about $2R_d$.

Each of the galaxy models was evolved in isolation to understand how an initially superthin galaxy would be restructured as result of internal evolution alone. The simulations were performed using the Gadget code (Springel et al. 2001) which uses a variant of the leapfrog method for the time integration. The gravitational forces between the particles are calculated using the BH tree algorithm with a tolerance parameter $\theta_{tol} = 0.7$. The integration time step used was $\approx 0.4$ Myr and the models were evolved for about 5 – 6 Gyr. The number of particles used for the halo and disk are $1.1 \times 10^6$ each, the bulge contains $10^5$ particles with a total of $2.2 \times 10^6$ particles for each model which is in accordance with the suggestion by Dubinski et al. (2000). The softening lengths for the various components were used so that the maximum force on each particle is nearly the same

| Galaxy models | $Q$ | $\frac{h_z}{R_d}$ | $M_d$ | $M_{M,d}$ | $R_c/R_d$ | $A_2/A_0$ |
|---------------|-----|------------------|-------|----------|-----------|---------|
| RHG041        | 1.97 | 0.27             | 2.00  | 4.73     | 1.05      | 0.165   |
| RHG040        | 2.23 | 0.34             | 1.86  | 7.67     | 1.70      | 0.33    |
| RHG053        | 2.31 | 0.30             | 1.05  | 11.93    | 0.90      | 0.082   |
| RHG052        | 2.33 | 0.62             | 1.43  | 14.47    | 2.07      | 0.37    |
| RHG102        | 2.56 | 0.37             | 1.28  | 12.94    | 0.80      | 0.15    |
| RHG114        | 2.97 | 0.26             | 1.59  | 10.17    | 1.25      | 0.13    |
| RHG057        | 2.98 | 0.39             | 0.86  | 22.53    | 1.03      | 0.21    |
| RHG034        | 3.15 | 0.25             | 1.92  | 6.50     | 0.81      | 0.154   |
| RCG051        | 1.21 | 0.41             | 4.64  | 6.75     | 1.88      | 0.524   |
| RCG051A       | 1.21 | 0.61             | 4.75  | 6.52     | 1.98      | 0.508   |
| RCG049        | 1.34 | 0.22             | 2.41  | 4.21     | 0.70      | 0.576   |
| RCG101        | 1.60 | 0.42             | 5.15  | 6.68     | 0.63      | 0.55    |
| RHG116        | 1.65 | 0.29             | 4.98  | 7.50     | 1.25      | 0.54    |
| RHG097        | 1.84 | 0.45             | 3.12  | 7.88     | 1.66      | 0.546   |
| RHG036        | 2.22 | 0.20             | 2.78  | 1.96     | 0.7       | 0.571   |
| RHG109        | 2.85 | 0.39             | 2.70  | 6.87     | 1.96      | 0.458   |

Table 1. Basic parameters for the model galaxies and bar strength (defined in section 4.2) computed at the end of 5 Gyr.
3 INTERNAL SOURCES OF DISC HEATING

In the absence of environmental influences such as tidal interaction, mergers or satellite infall, the evolution of superthin galaxies would strongly depend on the internal processes. In particular, vertical heating of stars could change the thickness of stellar discs and perhaps transform a superthin disc into a typical thin or even thick disc. Hence, it is important to identify and understand various internal sources that might be operative in heating the stars in superthin galaxies.

Amongst the internal sources of vertical heating the ones that could have been important for superthin galaxies are scattering due to giant molecular clouds (Jenkins & Binney 1990), substructures or clumpiness in the dark matter halo (Font et al. 2001; Ardil et al. 2003), bars and transient spirals and/or bending waves (Hunter & Toomre 1969; Saha et al. 2010). However, the low star formation rates suggest that the presence of many giant molecular clouds are unlikely in superthin galaxies. Heating due to substructures in the dark halo are shown to be not efficient because the masses of the substructures are unlikely to be more than $10^{11} M_\odot$ and the orbits of the substructures rarely passes close to the disc mid-plane (Font et al. 2001).

Damping of bending waves could, in principle, lead to vertical heating of stars in galaxies. A detailed study by Araki (1983) showed that a bare stellar slab can become prone to strong bending instability (or firehose instability) if $\sigma_z/\sigma_r < 0.293$. Some of the stellar discs in our simulation, indeed, have $\sigma_z/\sigma_r < 0.3$ but we have not noticed any strong bending mode. Possible reason could be that these discs have finite thickness and are embedded in spheroidal dark matter halo – both of which provide restoring force (proportional to the square of the total vertical frequency, in this context) to stabilize the bending modes (Nelson & Tremaine 1995a, Saha 2008, Sellwood 2013). In real galactic stellar discs, warps, although common, have small amplitudes (Saha et al. 2009) and are thought to rotate with a slow pattern speed (though not measured), see Nelson & Tremaine (1995a). As a consequence, an warp has a little energy (nearly equal to the kinetic energy of a single globular cluster) stored in it (Nelson & Tremaine 1995b) to contribute to the vertical heating.

In N-body simulation, two-body relaxation due to discreteness noise is a source of heating but the process is known to be suppressed with increasing the number of particles and a convergent behaviour is reached once a simulation contains a few million particles as suggested by Dubinski et al. (2009) and this has been explicitly tested in a previous paper by Saha et al. (2010). Note each model galaxy in our sample is composed of $2 \times 10^6$ particles (also mentioned in the previous section) in compliance with suggestion by Dubinski et al. (2009).

4 EVOLUTION OF SUPERTHIN GALAXIES

Galaxies are thought to evolve from late-type to early-type along the Hubble sequence either through secular evolution or by external influences or a combination of the two, in general. It is important to understand the rate at which galaxies evolve along such a sequence. The rate at which any late-type galaxies would evolve towards early-type would certainly depend on various factors such as star formation rate, the efficiency of redistributing energy and angular mo-
of a stellar disc can then be estimated using the relation

\[ h(r, z = 0) = \sqrt{2 \pi G \rho_{\text{mid}}(r)} \]  

where \( \sigma_z \) is the vertical velocity dispersion and \( \rho_{\text{mid}} \) is the mid-plane mass density of stars at a location \( r \). The initial density distribution of stars along the vertical direction is well approximated using a \( \text{sech}^2 \) law as \( \rho(r, z) = \rho_{\text{mid}}(r) \times \text{sech}^2(z/h_z) \) in our model galaxies. However, as a galaxy evolves, it forms bars, spiral arms or undergoes bending instability, the stars are basically subject to a time-dependent potential. Hence, the above relation for determining the scale height of a stellar disc might not hold true any more.

We determine the scale height of a stellar disc at any epoch during the evolution using the second moment of the volume density distribution as follows (Saha et al. 2009)

\[ H(r) = \frac{\int z^2 \rho(r, z) dz}{\int \rho(r, z) dz} \]  \hspace{1cm} (2)

In the above equation, \( \rho(r, z) \) is the azimuthally averaged density of stars at a location \((r, z)\) in the meridional plane. The scale height of the disc is obtained as \( H_z(r) = \sqrt{H(r)} \). Note that for a \( \text{sech}^2 \) density distribution, the method of second moment gives a value of the scale height which is \( 0.907 \times h_z \). The radial variation of \( H_z(r) \) would give the flaring information about the stellar disc. Initially, the radial variation of scale height of a stellar disc is flat (by construction) and during the subsequent evolution, the stellar discs show mildly flaring. In fact, previous work by Narayan & Jog (2002) argue that the scale height of stars in observed galaxies (such as NGC 891 and NGC 4565) are likely to be moderately flaring when one takes into account the gas self-gravity in the hydrostatic balance. Moderate flaring of stars are also required in order to explain the onset of warps in a number of nearby edge-on galaxies (Saha et al. 2009). In the current work, we ignore mild flaring of stars and compute the stellar scale height averaged over \( 3 - 4 \) disc scale lengths which is well outside the radial extent of the bar that forms in most of our stellar discs and use that value of scale height for subsequent analysis.

Throughout the text, we use thickness and/or scale height to indicate the same quantity defined in Eq. (2). Below we discuss detailed evolution of two initially superthin galaxies having same initial thickness that follows two entirely different evolutionary path.
4.2 Stellar discs with strong bar

More than 2/3 of the observed disc galaxies host strong bars in their central regions implying bars are common in disc galaxies (Eskridge et al. 2000; Barazza et al. 2008). However, the theoretical understanding of the formation and growth of bars in real galaxies is not yet clear (Sellwood 2013). N-body simulations, especially the work of Athanassoula (2002), has shown that a bar can grow stronger in the presence of a live dark matter halo and recent N-body simulations by a number of authors such as Dubinski et al. (2009), Sellwood & Debattista (2009), Klypin et al. (2009), reveal further insights on the role of dark matter halo mass distribution in the context of bar growth; while Saha & Naab (2013) showed the importance of halo spin on the bar formation. Once formed, a strong bar can grow stronger in the presence of a live dark matter halo and at about 2 Gyr in this model. A corresponding drop in the value of $A_2/A_0$ (here, $A_m$ denotes the $m^{th}$ order Fourier component of the surface density distribution) can be seen from Fig. 3. After the buckling phase, the disc progressively thickens as it is evident from the edge-on images taken at different epochs during the evolution (see Fig. 3). During this growing phase of the bar, the stars are subject to chaotic diffusion as shown by Brunetti et al. (2011). In order to find out the impact of this process, we follow the vertical density distribution of stars at several different locations in the disc and at several epochs during the evolution. It is important to notice that the disc contains apparently no spiral arms nor any bending modes beyond about 2 Gyr and mostly dominated by a bar which as mentioned above, is capable of stirring up the stars globally. Although the impact of a bar on the stars are more visible within the corotation radius, it is equally important to understand how the vertical distribution of stars changes outside this radial as a result of bar driven chaotic diffusion which is not limited to corotation region. Fig. 5 shows the initial ($t=0$) and final ($t=5.5$ Gyr) vertical density distribution of stars computed at $\sim 4 R_d$. This clearly demonstrates how bar alone can fatten the distribution of stars along the vertical direction and this primarily happens through the broadening of the velocity distribution function which was previously shown by Saha et al. (2010, 2013).

In Fig. 6, we show the evolution of the stellar scale height computed in a way explained in section 4.1. Our results show that the disc becomes thicker nearly by a factor of 3.7 in about 5.5 Gyr. In terms of kpc scale, the scale height of stars increases from 120 pc to $\sim 444$ pc over this time period and the stellar disc leaves the superthin regime. Notice that the disc does not have any apparent spiral arms associated with the bar nor any strong bending oscillations in the outskirts of the disc (see Fig. 3) which becomes hot enough for any of these features to survive over such a longer period of time.

We have carried out this analysis for the rest of the models which formed strong bars, see Fig. 4. All of these model galaxies were initially superthin and transformed to thin ones over about 5 Gyr. The bar strengths for each model are given in Table 1. An important message is that superthin galaxies are unlikely to host strong bars along their evolutionary path.

4.3 Stellar discs with weak bar

Looking at the weak bars (e.g., type SAB), it is not clear whether they are formed via partial dissolution of strong bars or due to some other mechanisms (Sellwood & Wilkinson 1993). Understanding the properties of weak bars, its formation and growth in real galaxies requires further investigation both in observation and numeri-

**Figure 5.** The vertical density distribution of stars for model RHG116. The blue dotted curve denotes the initial one and the red dotted curve after 5.5 Gyr computed at 4 disc scale lengths. $\rho(0)$ is the midplane density at the corresponding epoch.

**Figure 6.** The time evolution of stellar scale height in two models, RHG116 and RHG102. The green solid curve showing the scale height of stars which are heated by a strong bar as in model RHG116. The red dashed line represent the same but for the model RHG102.
Figure 7. Surface density maps of stellar discs which formed strong bars. For each model galaxy, we show three such maps: the upper most one at t=0 (edge-on), middle one at t=5 Gyr (edge-on) and bottom panel at t=5 Gyr (face-on). All the panel maps are scaled to same color scale.

The stellar disc of RHG102 is hot with $Q = 2.56$ (see Fig. 2 for the radial profile) and dark matter dominated. Fig. 8 shows the surface density maps at different epochs and the time evolution of the bar amplitude can be seen from Fig. 9. What we learn from these figures is that the growth of the bar in this model is very slow and remains weak till ~ 6 Gyr which is nearly half the Hubble time. Some of these models were run for even longer time e.g., RHG057 which did not grow any stronger bar (see, Saha et al. 2013). The edge-on view of the stellar disc in RHG102 shows no obvious sign of buckling instability because the bar is not self-gravitating enough and the disc lacks vertical inner Lindblad resonance (ILR) (Raha et al. 1991; Pfenniger & Friedli 1991). From the face-on view of this model galaxy, it is clear that this model has not formed any strong two-armed spiral and the edge-on view reveals no obvious bending oscillations either; altogether the stellar disc is able to maintain a smooth, featureless structure over a significant fraction of the Hubble time. This holds true for the rest of the model galaxies in our sample (see, Fig. 7) which grow nothing but weak bars over a longer period of time.

The time evolution of the stellar disc thickness in model RHG102 can be seen from Fig. 8. The thickness increases roughly by a factor of 2 in 2.5 Gyr and remained nearly unchanged till about 6 Gyr - indicating a very slow heating process. In terms of kpc scale, the final scale height of stars at 5.5 Gyr is ~ 256 pc indicating that the stellar disc can be considered as one of superthin category. Note that the stellar disc of our Milky Way has a scale-height of about 400 pc. The vertical density distribution of stars at 5.5 Gyr resembles quite well the initial $sech^2$ profile (see Fig. 10). In other words, the vertical density near the mid-plane changes quantitatively by a very small amount. It turns out that a plausible evolutionary scenario for the superthin galaxies is that they grow weak bars in the central region and are evolving on a very slow secular evolution time scale. One could, in principle, argue that the observed superthin galaxies might not be forming even weak bars; but the point we are making here is that it is hard for a galaxy to remain completely axisymmetric over a Hubble time as demonstrated for a range of models in Fig. 9.
Here, we investigate how these galaxies are distributed in the parameter space spanned by the thickness of stars and bar strength. We carry out this exercise at different epochs over a period of 5–6 Gyr. The initial and final disc thickness are computed using the method described in section 4.1. We calculate the initial bar strength (considered as the peak of $A_2/A_0$) when the disc has been evolved by an orbital time (which is $\sim 300$ Myr). Here orbital time is measured at the disc half-mass radius. The final bar strength is calculated at around 5–6 Gyr. Fig. 11 shows the initial and final bar strengths and their corresponding stellar thickness measurements. Initially, all the model galaxies are essentially superthin i.e., $H_\ast/R_d < 0.1$. Galaxies that formed strong bars leave the superthin regime in 5–6 Gyr time scale transforming into typical thin discs. In contrast, galaxies that host weak bars remained superthin even after 5–6 Gyr of evolution. There seems to be a continuous well defined trend (see Fig. 11) in which the thickness of a galaxy’s stellar disc
Figure 10. Same as in Fig. 5 but for the model RHG102.

Figure 11. Galaxy evolution in the parameter space spanned by bar strength and stellar thickness. Initial $A_2$'s are measured within $T_{orb}$. The red open circles (initial models) are evolved into filled red circles and blue open triangles (initial models) are evolved into filled blue triangles in 5−6 Gyrs.

The strength and long-term evolution of a bar are intricately related to the dark matter distribution in the host galaxy, especially in the central region (Athanassoula 2003; Dubinski et al. 2003). In this subsection, we examine whether the growth and final strength of a bar (which eventually thicken the stellar disc) depends explicitly on the core radius ($R_c$) of the surrounding dark matter halo. In Fig. 12 we show the thickness of all the stellar discs and the corresponding $R_c/R_d$ values of the dark matter haloes calculated at the end of 5−6 Gyrs. For our galaxy models, the values of $R_c/R_d$ vary from as low as $\sim 0.5$ to about 2.1. What we find is that the dark matter haloes of superthin galaxies can have a wide range of halo core radius; the same applies to galaxies that are classified as thin ones in their final state.

It appears that the galaxies in our sample that maintained their superthinness over 5−6 Gyr showed no strong preference for any particular dark matter haloes.

By studying the hydrostatic equilibrium of stars in the presence of gas and dark matter halo, Banerjee & Jog (2013) suggest that the dark matter halo in UGC 7321 is compact with $R_c/R_d = 1.38$. This is in accordance with what we have found i.e., all of our final superthin galaxies have $R_c/R_d < 2$ except one with $R_c/R_d \approx 2.1$. What is intriguing is that even thin/thicker galaxies could be surrounded by such compact haloes. It is worth mentioning that UGC 7321 is an well-studied case of superthin galaxies (Matthews et al. 1999; Matthews 2000). Their study suggests that the superthin galaxy UGC 7321 is an underevolved system both in dynamical and star forming sense. From the disc colors and color gradients, they also indicate that UGC 7321 is not a young galaxy. There is a population of old disc stars above the disc midplane indicating some ongoing dynamical heating in the galaxy. Our study suggests that weak bars could be responsible for a slow heating of the stars in the galaxy. In fact, the position velocity diagram in HI line (Uson & Matthews 2003) and the deviation of the light profiles in the inner region, the shape of the isophotes in R-band (Pohlen et al. 2003)—all together indicate that there might be a thin bar hidden in the galaxy, UGC 7321. Based on our present analysis, we can comment that such a thin bar (if present in UGC 7321) must be weak; otherwise it would have gone through a bar buckling instability transforming the superthin disc to a thin one.

5 DISCUSSION AND CONCLUSIONS

The very presence of smooth, featureless superthin galaxies in our local universe suggest that they are not subject to strong minor mergers or significant accretion events, as otherwise they would either be destroyed or converted to thicker disc galaxies (Toth & Ostriker 1992; Purcell et al. 2000). And if they are isolated as observation indicates, they...
should be subject to disc heating arising due to the internal sources mentioned in section 3. Obviously, if we could switch off some of these heating sources, the issue of maintainance of superthinness could be resolved. Our simulations suggest that this is unlikely as stellar discs, with diverse initial condition, form either strong or weak bars both of which heat stars but of course, with varying efficiency. On the other hand, the apparently smooth, flat stellar discs also indicate that SGs are unlikely to host strong bars as otherwise such discs eventually would have to face a buckling instability (see Sellwood 2013 for coherent review). The other possibility, which can not be ruled out unambiguously, is that SGs do form weak bars over a longer time scale (as shown by our simulations).

The question arises on the validity of the initial condition that we assume. Were progenitors of present day superthin galaxies really radially hot? If yes, how those progenitors achieved such a radially hot discs? The answer, of course, remains unknown as it depends on how these galaxies were actually formed. We speculate that during the early phase of galaxy formation, an extremely thin disc would have gone through strong spiral instabilities and the amount of preferential radial heating produced by it, would have self-destroyed the spiral arms leaving a red-hot dead disc. The low star formation rates as suggested by Matthews et al. (1999), indicates that the present day superthin galaxies are radially hot preventing them from forming further strong non-axisymmetric instabilities. Then our study shows that during the course of secular evolution such radially hot stellar discs when embedded in a massive live dark matter halo form only weak bars. In other words, our simulations suggest that weak bars are perhaps the maximal non-axisymmetric features that a self-consistent superthin galaxy might be able to support if left isolated for several billion years.

Our main conclusions from the present work are the following:

1. We show that an initially thin stellar disc is able to maintain its thinness over several billion years if it hosts a weak bar. Such weak bars heat the stars very slowly and can increase the stellar scale-height roughly by a factor of 2 in about 5–6 billion years.

2. Our simulations suggest that superthin discs with strong bars are unlikely as well as weak bars making thicker discs. There seems to be a good correlation between the thickness of a stellar disc and the amplitude of the bar it hosts.

3. Our results show that there is no strong preference for smaller halo core radii amongst superthin galaxies. Thicker discs could also reside in halos with smaller core radii. However, our study do not cover a wide range of halo core radius to disc scale length ratios.

4. We show that during the course of evolution, the underlying nature of the vertical density profile in a model hosting a weak bar remains unchanged except fattening by a small amount.

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