Simulating disc galaxy bulges that are consistent with observed scaling relations

C. R. Christensen,1* A. M. Brooks,2 D. B. Fisher,3,4 F. Governato,5 J. McCleary,6 T. R. Quinn,5 S. Shen7 and J. Wadsley8

1Department of Astronomy, University of Arizona, 933 North Cherry Avenue, Rm. N204, Tucson, AZ 85721-0065, USA
2Department of Physics & Astronomy, Rutgers, The State University of New Jersey, 136 Frelinghuysen Rd, Piscataway, NJ 08854, USA
3Centre for Astrophysics and Supercomputing, Swinburne University, Hawthorn, VIC 3122, Australia
4Department of Astronomy, University of Maryland, CSS Bldg., Rm. 1204, Stadium Dr., College Park, MD 20742-242, USA
5Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
6Department of Astronomy, New Mexico State University, PO Box 30001, MSC 4500, Las Cruces, NM 88003-8001, USA
7Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
8Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4L8, Canada

ABSTRACT
We present a detailed comparison between the photometric properties of the bulges of two simulated galaxies and those of a uniform sample of observed galaxies. This analysis shows that the simulated galaxies have bulges with realistic surface brightnesses for their sizes and magnitude. These two field disc galaxies have rotational velocities \(~100\) km s\(^{-1}\) and were integrated to a redshift of zero in a fully cosmological \(\Lambda\) cold dark matter context as part of high-resolution smoothed particle hydrodynamic simulations. We performed bulge-disc decompositions of the galaxies using artificial observations, in order to conduct a fair comparison to observations. We also dynamically decomposed the galaxies and compared the star formation histories of the bulges to those of the entire galaxies. These star formation histories showed that the bulges were primarily formed before \(z = 1\) and during periods of rapid star formation. Both galaxies have large amounts of early star formation, which is likely related to the relatively high bulge-to-disc ratios also measured for them. Unlike almost all previous cosmological simulations, the realistically concentrated bulges of these galaxies do not lead to unphysically high rotational velocities, causing them to naturally lie along the observed Tully-Fisher relation.

Key words: methods: numerical-- galaxies: bulges-- galaxies: formation-- galaxies: spiral-- galaxies: structure.

1 INTRODUCTION
Computational astronomers have made great strides in reproducing the observed disc structure of spiral galaxies in \(\Lambda\) cold dark matter simulations, as studies of the Tully-Fisher relation (Robertson et al. 2004; Governato et al. 2007; Stinson et al. 2010; Piontek & Steinmetz 2011), angular-momentum content (Scannapieco et al. 2009), and disc sizes (Brooks et al. 2011) have shown. Historically, though, the corresponding bulges of simulated galaxies were much too large and concentrated compared to observed bulges (Binney, Gerhard & Silk 2001; Bullock et al. 2001; van den Bosch 2001; van den Bosch et al. 2002; D’Onghia et al. 2006; D’Onghia & Navarro 2007; Stinson et al. 2010; Scannapieco et al. 2012). This difficulty in reproducing the bulges of disc galaxies represents the more-persistent aspect of the ‘angular-momentum catastrophe’ (Navarro & White 1994).

In the past several years, only a handful of simulations have been able to combine the resolution necessary to resolve bulges in cosmological simulations with star formation and feedback models capable of producing galaxies with realistic mass bulges. These simulations have variously succeeded by limiting the star formation efficiency (Agertz, Teyssier & Moore 2010), pre-heating the gas through early stellar feedback (Stinson et al. 2012), or increasing the strength of supernova-driven (SN-driven) outflows, either by scaling a kinetic wind model (Okamoto 2012; Vogelsberger et al. 2013) or concentrating the energy through a high star formation threshold (Brook et al. 2011; Guedes et al. 2011). Similar strong outflows have been shown to reduce the amount of low-angular-momentum material (Pontzen & Governato 2012), resulting in bulgeless or cored dwarf galaxies (Oh et al. 2011; Governato et al. 2012; Teyssier et al. 2013) and disc galaxies with realistic, rising rotation curves...
We then subdivided the spheroidal component into the bulge and halo stars by making a radial cut where the spheroid mass profile changed to a shallower slope. This process is sensitive to the obscuring effects of dust and the face-on orientation provides the most accurate fit. We determined the surface brightness profiles through ellipse fitting using the routine of Bender & Moellenhoff (1987). During this ellipse fitting, the radial sizes of ellipses were optimized to maintain a roughly constant signal-to-noise ratio across the profile. For every galaxy, we also fitted isophotal ellipses to the images with the software of Lauer (1985), which is a Fourier-based ellipse fitting method. We then averaged together the isophotes from both the Bender & Moellenhoff (1987) and Lauer (1985) routines.

The bulge–disc decompositions were determined by fitting two components, a Sérsic bulge plus outer exponential disc, to the major axis surface brightness profile. The inner radius cut for the fit was chosen to be 200 pc (approximately the softening length), and the outer radius cut was set to the location where the profile broke from a smoothly varying exponential. The values of the bulge and disc magnitudes, the half-light radius of the bulge (\(r_h\)) and the disc scalelength (\(r_s\)), the Sérsic index, and the \(B/T\) ratio are listed in Table 1. Neither galaxy shows evidence of a bar at a redshift of zero.

### 2.2 Photometric decompositions

Simulated observations of the galaxies were created using the Monte Carlo radiative transfer code, SUNRISE (v 3.6; Jonsson 2006). The magnitudes and photometric images of our galaxies in Johnson (1966) and Two Micron All Sky Survey (2MASS; Cohen, Wheaton & Megeath 2003) bands (Table 1) were calculated by convolving the generated spectral energy distribution with the filter transmission curves. We decomposed the SUNRISE-generated photometric images of the galaxies into bulge and disc components using the same analysis discussed in detail in Fisher & Drory (2008). We opted to use the face-on 2MASS \(H\)-band images, as infrared data are less sensitive to the obscuring effects of dust and the face-on orientation provides the most accurate fit. We determined the surface brightness profiles through ellipse fitting using the routine of Bender & Moellenhoff (1987). During this ellipse fitting, the radial sizes of ellipses were optimized to maintain a roughly constant signal-to-noise ratio across the profile. For every galaxy, we also fitted isophotal ellipses to the images with the software of Lauer (1985), which is a Fourier-based ellipse fitting method. We then averaged together the isophotes from both the Bender & Moellenhoff (1987) and Lauer (1985) routines.

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3 RESULTS

3.1 Bulge photometric properties

Elliptical galaxies follow robust scaling relations between surface brightness, luminosity, and half-light radii. The bulges of disc galaxies, however, are more varied. While classical bulges follow the elliptical galaxy scaling relations, pseudo-bulges tend to have lower surface brightnesses for the same size or magnitude (Gadotti 2009; Fisher & Drory 2010). In contrast to both classical and pseudo-bulges, simulated bulges have historically been too bright and concentrated, leading them to have higher surface brightnesses than predicted by the observed scaling relations.

Here, we compare the photometric properties of the simulated bulges to those of an observed sample of disc and elliptical galaxies, and the associated scaling relations (Fisher & Drory 2010; Fisher et al. 2013). This sample includes disc galaxies from Hubble types of Sa–Sd and, therefore, covers the range of bulge properties. It also covers a similar range in $R - V$ as large surveys of galaxies, such as de Vaucouleurs et al. (1991), and preferentially samples bright and large disc galaxies in which bulges are more commonly found. Critically, the photometric decompositions of the simulated galaxies followed exactly the same process as the observed galaxies. Fig. 1 shows the bulge $B$-band surface brightnesses, magnitudes, and half-light radii of the simulated and observed galaxies. The simulated galaxies lie among the observed galaxies when examining both size versus surface brightness and magnitude versus surface brightness, indicating that the bulges of the simulated galaxies are not overly concentrated. One of the galaxies, h986, lies slightly outside the observed galaxies in the magnitude versus size plot, although within the error. The relatively large size of its bulge indicates that, if anything, it is not concentrated enough and may be evidence of overcorrection on the part of the simulations.

The Sérsic indices of the simulated galaxies (1.65 and 2.53) are consistent with those determined for the observed sample of disc galaxies, which had a median value of 1.86 and a standard deviation of 1.0. In addition to examining the bulge properties, we also determined the disc scalelengths and magnitudes. The disc scalelengths for similar magnitude discs in the observed sample range between 800 and 3900 pc. The disc scalelength of the simulated galaxy, h603, is 2700 pc and consistent with these disc scalelengths. The disc scalelength of h986 is highly uncertain and can vary by a factor of several. The length listed in Table 1 (5400 pc) is larger than that of galaxies with similar disc magnitudes. However, when $B$-band images of it were decomposed, the disc was found to be consistent with the observed size versus magnitude relation (Brooks et al. in preparation).

Both simulated galaxies have large $B/T$ values in the $H$ band: 0.43 and 0.53. Because of the lack of recent star formation in the bulge, these values are lower in bluer bands. For instance, decompositions of $B$-band images yield $B/T$ values of 0.28 and 0.34. While not entirely unheard of for galaxies of this mass, these ratio are at the far upper extreme. For instance, in the comparison observational sample, most galaxies with magnitudes within 0.3 mag of the simulated galaxies had $B/T$ values between 0.05 and 0.1, with only one outlier having $B/T$ equal to 0.4. This discrepancy indicates that while the shape of the bulges is correct, other processes may be required to reduce the bulge mass.

3.2 Star formation histories

Bulges have older average stellar ages than discs, implying that a large fraction of their stellar mass was formed comparatively early (Allen et al. 2006; MacArthur, González & Courteau 2009). Furthermore, delayed star formation results in more gas-rich mergers and smaller bulges (Hopkins et al. 2009). The bulge properties should, therefore, be related to the star formation histories (SFH) of the galaxies and their bulges (Fig. 2). We used kinematic decomposition to select individual bulge star particles, which resulted in a slightly different component selection than photometric decomposition. For instance, the $B/T$ ratios produced by the kinematic decompositions were 0.57 and 0.56, as opposed to 0.43 and 0.53 (see Scannapieco et al. 2010).

During periods of peak star formation (generally following the onset of mergers, as indicated by grey bars in the plot), bulge stars were predominantly formed. In C12a, we found that during such peak star formation times, SN-driven outflows were very effective at driving out low-angular-momentum gas, which would have limited bulge growth. Additionally, almost all bulge star formation happened within the first 7 Gyr for both galaxies. While both galaxies lie along the observed redshift–stellar mass relation (Munshi et al. 2013), abundance matching from Moster, Naab & White (2013) indicates that these simulations may have excessive high-z star formation. For instance, Moster et al. (2013) predict that for galaxies of this mass, half the stellar mass will have been formed at redshift 0.25, whereas for these simulations, half the stellar mass was formed by redshifts 1.15 and 1.00. Reducing the amount of high-redshift star formation would likely bring the $B/T$ ratios closer to the observed values.
Examining the bulge SFHs raises the question of whether these galaxies have classical bulges or pseudo-bulges. The SFHs of both simulated galaxies show at least some evidence of the merger-driven growth associated with classical bulges (Kormendy & Ho 2013). The position of both simulated galaxies along the scaling relations is typical of classical bulges but still consistent with pseudo-bulges. These two factors combined with a Sérsic index of 2.53 indicate that h1986 is most likely a classical bulge. The lower Sérsic index of h963 (1.65), however, is more consistent with a pseudo-bulge. When considered in light of its heightened star formation following mergers and its position along the scaling relations, h963 could be a composite pseudo-classical bulge (Fisher & Drory 2010).

3.3 Tully–Fisher relation

In order to ensure that reducing the central concentration of the bulge through feedback did not disrupt the discs, we compared the simulated galaxies to the observed stellar and baryonic Tully–Fisher relations from McGaugh (2005, Fig. 3). As in McGaugh (2005), stellar masses were determined from the SUNRISE-generated B-band magnitudes and $B - V$ colours of the galaxies, and gas masses were calculated by totalling the H I mass within the disc and multiplying by 1.4 to account of He I. We also include data points representing the actual stellar mass; the difference between the actual and observationally determined stellar masses was previously discussed in Munshi et al. (2013). $V_f$ was defined to be the average rotational velocities of gas in the outer portion of the gas disc (the radii that contained 80–90 per cent of the disc gas). As these galaxies have flat rotation curves (C12a), $V_f$ was largely insensitive to the measurement radii. Both simulated galaxies lie along the baryonic and stellar Tully–Fisher relations, indicating that, in addition to realistically concentrated bulges, they have appropriate disc stellar and gas masses. The match to the observed relations is also a strong indication that the simulated galaxies had the correct distribution of matter – too high a concentration of baryons would have resulted in a peaked rotation curve and too large of $V_f$ for its stellar and baryonic masses.

4 CONCLUSIONS

In this Letter, we have taken an observationally motivated approach to analyse the bulges of two simulated galaxies, previously shown to have rising rotation curves (C12a). We photometrically decomposed H-band images into bulge and disc components and compared the bulge properties to an observational sample of disc and elliptical galaxies. We determined that these simulations had bulges of the appropriate surface brightness for their magnitude and size. This success indicates that the centres of the simulated galaxies have appropriate stellar distributions and that they are not overly concentrated. Their relatively high bulge-to-total ratios, however, remain a concern and demonstrate a need for a further reduction in the central stellar mass. In particular, reducing the amount of early star formation could both lower the bulge mass and result in more realistic SFHs.

We compared the SFHs of the kinematically selected bulges to those of the entire galaxies. We found that the bulges formed primarily during the first half of the galaxies’ lifetimes and that bulge star formation occurred during periods of peak star formation, possibly driven by mergers. Of the two galaxies, the SFHs and photometric properties of one were most consistent with the properties of classical bulges, while the other shared characteristics with both classical and pseudo-bulges. Finally, we verified the global structure of the simulated galaxies by comparing them to the observed baryonic and stellar Tully–Fisher relations.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous referee for the suggestions. These simulations were run at NASA AMES and Texas Supercomputing Center. CC acknowledges support from NSF grants AST-0908499 and AST-1009452. FG acknowledges support from HST GO-1125 and NSF AST-0908499. TQ acknowledges support from NSF grant AST-0908499. We made use of pynbody (https://github.com/pynbody/pynbody) in our analysis.
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