Galaxies Grow Their Bulges and Black Holes in Diverse Ways

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Abstract

Galaxies with Milky Way–like stellar masses have a wide range of bulge and black hole masses; in turn, these correlate with other properties such as star formation history. While many processes may drive bulge formation, major and minor mergers are expected to play a crucial role. Stellar halos offer a novel and robust measurement of galactic merger history; cosmologically motivated models predict that mergers with larger satellites produce more massive, higher-metallicity stellar halos, reproducing the recently observed stellar halo metallicity–mass relation. We quantify the relationship between stellar halo mass and bulge or black hole prominence using a sample of 18 Milky Way-mass galaxies with newly available measurements of (or limits on) stellar halo properties. There is an order of magnitude range in bulge mass, and two orders of magnitude in black hole mass, at a given stellar halo mass (or, equivalently, merger history). Galaxies with low-mass bulges show a wide range of quiet merger histories, implying formation mechanisms that do not require intense merging activity. Galaxies with massive “classical” bulges and central black holes also show a wide range of merger histories. While three of these galaxies have massive stellar halos consistent with a merger origin, two do not—merging appears to have had little impact on making these two massive “classical” bulges. Such galaxies may be ideal laboratories to study massive bulge formation through pathways such as early gas-rich accretion, violent disk instabilities, or misaligned infall of gas throughout cosmic time.

Key words: galaxies: bulges — galaxies: evolution — galaxies: general — galaxies: halos — galaxies: stellar content

1. Introduction

Galaxies with stellar masses comparable to the Milky Way ($M_\star \sim 6 \times 10^{10} M_\odot$)—MW peers hereafter—host the majority of the stellar mass in the present-day universe (Papovich et al. 2015). This mass range exhibits the greatest diversity in galaxy morphology and star formation activity for galaxies in the centers of their own halos, from nearly bulgeless star-forming galaxies like the Milky Way or M101 through to elliptical or lenticular galaxies like Centaurus A or the Sombrero. Furthermore, the mass of the bulge broadly correlates with black hole (BH) mass (Kormendy & Ho 2013). In turn, the BH mass strongly correlates with star formation activity—the more prominent the BH, the more quiescent the galaxy (Terrazas et al. 2016).

What drives the growth of MW peers bulges and BHs? It is often argued that massive, centrally concentrated “classical” bulges are the result of major or minor merger activity, whereas less massive, less centrally concentrated pseudobulges may be the result of disk instabilities and bar evolution (e.g., Kormendy & Kennicutt 2004). Many galaxy formation models explicitly appeal to mergers to form bulges and BHs (e.g., Hopkins et al. 2010; Somerville & Davé 2015). Indeed, it has been clear for decades that at least some elliptical galaxies are merger products (Toomre 1977; Rothberg & Joseph 2006). Yet, other viable formation paths remain, e.g., early formation of a central bulge in a chaotic collapse (e.g., Johansson et al. 2012), the formation of bulges through violent disk instabilities in early gas-rich disks (e.g., Ceverino et al. 2015), or the formation of bulges from dramatic changes in the angular momentum of successive generations of accreted gas (Sales et al. 2012). Indeed, given the active merging and accretion characteristic of a CDM universe, and the relative infrequency of large bulges in the local universe (Kormendy et al. 2010), current generations of hydrodynamical models appear to dramatically overproduce bulges (e.g., Somerville & Davé 2015; Brooks & Christensen 2016). While simulators explore possible processes to suppress bulge formation (see, e.g., Brooks & Christensen 2016), it is clear that observational insight into the relationship between galaxy merging and bulge growth is urgently required.

The outskirts of galaxies give particular insight into their merger histories. While gas in mergers can lose angular momentum and fall into the central parts of galaxies (e.g., Robertson et al. 2005), stars in merging galaxies are collisionless. Stars in low-mass satellite galaxies are easily tidally torn from their parent satellite and are spread out into a diffuse stellar halo (e.g., Bullock & Johnston 2005; Cooper et al. 2010). The stellar mass of galaxies is a strong function of dark matter halo mass; accordingly, the mass of the resulting stellar halo is dominated by the largest few disrupted satellites (e.g., Purcell et al. 2007). Since galaxies show a strong relationship between their metallicity and stellar mass (Kirby et al. 2013), stellar halos are predicted to and indeed show a strong correlation between their metallicity and mass (Deason et al. 2016; Harmsen et al. 2017; Section 3). Merging with larger satellites may modify this trend by kicking up in situ stars from the central galaxy via tidal tails or violent relaxation (e.g., Watkins et al. 2015). These stars will augment the overall population and will tend toward being metal-rich, preserving
the overall trend toward bigger satellites producing more massive and metal-rich stellar halos.

Thus, it is important to probe correlations between the stellar halo mass—a sensitive record of galactic merger history—and the prominence of a galactic bulge and its supermassive BH. Yet, stellar halo masses have been challenging to measure owing to their extremely low surface brightnesses, fainter than 30 V-band mag arcsec$^{-2}$. Recently, imaging of diffuse light from halos permitted detection of relatively massive halos (e.g., Merritt et al. 2016; Trujillo & Fliir 2016). In parallel, observationally expensive studies of resolved, typically red giant branch (RGB), stars in the outskirts of nearby galaxies reach fainter equivalent surface brightness limits and give estimates of both stellar halo masses and typical metallicities (Radburn-Smith et al. 2011; Ibata et al. 2014; Rejkuba et al. 2014; Peacock et al. 2015; Monachesi et al. 2016a; Harmsen et al. 2017).

The goal of this Letter is to use these recent measurements of stellar halo masses and metallicities as a new probe of the relationship between galactic merger histories, bulges, and supermassive BHs. We focus on galaxies that are the main/central one in their dark matter halos with total stellar masses in the range $(3–12) \times 10^{10} M_\odot$. After reviewing observational estimates of stellar halo properties and bulge/BH masses in Section 2 for a sample of 18 galaxies—the only ones currently with suitable stellar halo measurements or limits—we then show that there is little correlation between merger history and bulge or BH prominence (Section 3). We explore this issue further and review our main conclusions in Section 4.

2. The Data

We use estimates of total stellar halo mass and a representative stellar halo metallicity for this work. Stellar halo masses and metallicities are unavoidably ambiguous measurements—both the bulge and stellar halo are kinematically hot and may be difficult to separate, and while the stellar halo is more likely to be accretion-dominated and the bulge in-situ-dominated, both components are expected to have contributions from both accretion and in situ star formation (Zolotov et al. 2009). While this highlights the importance of fairly connecting simulations and observations, current efforts have not yet reached this goal. Therefore, we take a simple approach that is easy for simulators to model.

Observations typically measure the extended diffuse component at galactocentric minor axis distances between 10–40 kpc and >20 kpc along the major axis (Merritt et al. 2016; Harmsen et al. 2017). We extrapolate “aperture” stellar halo masses within this radial range to total stellar halo mass using accreted stars in cosmologically motivated models. Such extrapolations are inherently uncertain and may vary with merger history or bulge prominence (Rodríguez-Gomez et al. 2016; Amorisco 2017). We explore this issue using accreted stellar halos of >1200 galaxies with $M_*$ between $(3–10) \times 10^{10} M_\odot$ in the Illustris hydrodynamical model (Rodríguez-Gomez et al. 2016). The total accreted stellar halo mass is $\sim 3 \times$ the “aperture” accreted mass with a scatter of 40% and <15% systematic variation across the range of halo masses and galaxy morphologies. These results agree quantitatively with our analysis of Bullock & Johnston (2005) models (Harmsen et al. 2017) and preliminary analysis of the accreted halos of MW peers in the high-resolution Auriga hydrodynamical simulations (A. Monachesi 2017, in preparation). We adopt this extrapolation and its uncertainties in what follows.

As hydrodynamical simulations that have both accreted and in situ components find that minor axis metallicity profiles at galactocentric radii $>15$ kpc are uncontaminated by in situ material (Monachesi et al. 2016b), we choose to estimate stellar halo metallicity at a minor axis distance of 30 kpc (corresponding to $\sim 1/10$ of the virial radius).

Six galaxies in our sample have resolved stellar populations information for their stellar halos from the Galaxy Halos, Outer disks, Substructure, Thick disks and Star clusters (GHOSTS) survey (http://vo.aip.de/ghosts/survey.html; Radburn-Smith et al. 2011; Monachesi et al. 2016a). RGB stars count allowed GHOSTS to reach V-band (Vega) surface brightness sensitivities of $\sim 33$ mag arcsec$^{-2}$, revealing roughly power-law stellar halos between minor axis distances of 10 kpc to $>50$ kpc. These profiles were integrated within the observed range of radii and extrapolated to total stellar halo mass as discussed above. The RGB color is sensitive to stellar halo metallicity (Monachesi et al. 2016a), and we adopt a derived [Fe/H] value at 30 kpc along the minor axis following the observational calibration of [Fe/H] as a function of RGB colors for globular clusters (Streich et al. 2014) assuming $\alpha$/Fe = 0.3.

We add stellar halo masses and metallicities at 30 kpc along the minor axis for the MW (Sesar et al. 2011; Xue et al. 2015; Bland-Hawthorn & Gerhard 2016), M31 (Gilbert et al. 2014; Ibata et al. 2014), and NGC 3115 (Peacock et al. 2015; Peacock et al. 2015) estimated a mass in low-metallicity stars in NGC 3115 of $(3–10) \times 10^{10} M_\odot$, which they adopted as an estimate of the stellar halo mass. As there is a considerable population of high-metallicity stars at large radii in NGC 3115, which could be argued to legitimately belong to its stellar halo, we choose to adopt $1.5 \times 10^{10} M_\odot$ as a lower limit to its halo mass. No published estimate of stellar halo mass exists for Cen A; we adopt the metallicity along the minor axis at 30 kpc from Rejkuba et al. (2014).

Stellar halo masses (for UGC 180, NGC 1084, NGC 2903, and NGC 4220) or upper limits (for NGC 3351, NGC 3368, NGC 4258, and M101; galaxies that were either presented as upper limits or detections with $1 \sigma$ error bars overlapping with zero) are adopted from Trujillo & Fliir (2016; UGC 180) and Merritt et al. (2016). The stellar halo masses from Merritt et al. (2016) are extrapolated to total stellar mass as described above and as tabulated by Harmsen et al. (2017). As these halo masses were constrained using integrated light, these galaxies have no stellar halo metallicity estimates. Total stellar masses were adopted from the source papers, adjusted to a universally applicable Chabrier (2003) stellar IMF. Bulge-to-total ratios were derived from near-IR (K-band or longer) photometry from a variety of sources (described in Table 1; for Cen A we assume B/T = 1 and UGC 180’s B/T was roughly estimated to be $\sim 0.1 \pm 0.05$). Typical differences between independent estimates for the same galaxies are $\Delta(B/T) \sim 0.1$, comparable to the quoted uncertainties. BH masses and uncertainties (or limits) were adopted primarily from Kormendy & Ho (2013), where again the source papers are tabulated in Table 1.

3. Little Correlation between Stellar Halo, Bulge, and Black Hole Properties

One of the foundational assumptions of this work is that the stellar halo mass or metallicity is a reliable record of the merger
history of a galaxy. We examine this assumption in Figure 1. There is a strong correlation between the observed stellar halo masses and their metallicities at 30 kpc along the minor axis (Harmsen et al. 2017). This correlation is a generic prediction of accretion-only models, driven by the metallicity—mass relation of the disrupted satellite galaxies (Deason et al. 2016; Harmsen et al. 2017). Quantitative insight can be gained by comparison with a set of modeled stellar halos in 10^{12} M_{\odot} dark matter halos from Deason et al. (2016, squares). These models are color-coded by the mass weighted mean stellar mass of all of the contributing satellites to the halo (termed “typical” satellite mass hereafter), illustrating that the stars in more massive stellar halos primarily hail from more massive, more metal-rich satellite galaxies. The “typical” satellite mass is a tight function of the stellar halo mass, and we provide an approximate mapping on the ordinate in blue. We give also an approximate merger ratio assuming a main galaxy mass at the time of merger of \~\~ 3 \times 10^{10} M_{\odot} in green. The observation of this expected correlation strongly suggests that indeed the stellar halo encodes the merger history of galaxies and that we can now broadly infer the masses of the largest satellites that were accreted by or merged into our nearby neighbors.

We can now explore how MW peer merger history correlates with bulge and BH prominence. The main results are shown in Figure 2 where we show the bulge mass (left) and BH mass (right) as a function of stellar halo mass. For completeness, we show bulge mass and BH mass as a function of stellar halo metallicity in the top panels of Figure 3, and B/T ratio in the lower panels as a function of stellar halo mass (left) and metallicity (right). Both stellar halo mass and metallicity reflect the merger history of a galaxy as galaxies with bigger stellar halos merged with/accreted larger progenitors. No significant correlations between bulge/BH masses and stellar halo masses are seen in this data set. Galaxies with M_{stellar, halo, tot} > 10^{9} M_{\odot} or [Fe/H]_{30 kpc} > -1.2 have an order of magnitude spread in B/T ratio or bulge mass and two orders of magnitude spread in BH mass. All of the relations have Spearman rank correlation

### Table 1

| Name          | Stellar Mass (10^{10} M_{\odot}) | Stellar Halo Mass (10^{10} M_{\odot}) | Stellar Halo [Fe/H] (dex) | B/T | Black Hole Mass (10^{9} M_{\odot}) | References |
|---------------|----------------------------------|---------------------------------------|----------------------------|-----|-----------------------------------|------------|
| Milky Way     | 6.1                              | 0.55 ± 0.15                           | −1.7 ± 0.1                 | 0.2 ± 0.075 | 4.3 ± 0.36                        | 1, 2, 3, 4, 5 |
| M31           | 10.3                             | 15 ± 5                                | −0.75 ± 0.2                | 0.32 ± 0.11^a | 143_{31}^{143}                    | 6, 7, 8, 9, 10, 5 |
| NGC 253       | 5.5                              | 4.3 ± 2                               | −1.05 ± 0.1                | 0.28 ± 0.14 | <7                                 | 11, 8, 12, 13 |
| NGC 891       | 5.3                              | 2.7 ± 1.1                             | −1.0 ± 0.1                 | 0.2 ± 0.05  | ...                                | 11, 8, 14   |
| M81           | 5.6                              | 1.1 ± 0.5                             | −1.3 ± 0.1                 | 0.46 ± 0.15 | 65_{15}^{65}                       | 11, 8, 12, 5 |
| NGC 4565      | 8.0                              | 2.2 ± 0.9                             | −1.2 ± 0.1                 | 0.25 ± 0.05 | ...                                | 11, 8, 15   |
| NGC 4945      | 3.8                              | 3.5 ± 1.4                             | −0.85 ± 0.1                | 0.075 ± 0.025 | 1.35_{0.68}                       | 11, 8, 5    |
| NGC 7814      | 4.5                              | 6.4 ± 2.6                             | −1.05 ± 0.1                | 0.85 ± 0.15 | ...                                | 11, 8, 12   |
| Cen A         | 11.2                             | ...                                   | −0.43 ± 0.1                | 1_{0.0}^{1.0} | 57 ± 10                           | 5, 16       |
| NGC 1115      | 10.5                             | >15                                   | −0.6 ± 0.2                 | 0.8 ± 0.1^a | 897_{277}^{897}                   | 5, 17       |
| UGC 180       | 13.0                             | 4.0 ± 2.4                             | ...                       | 0.1 ± 0.05  | ...                                | 18          |
| NGC 1084      | 4.3                              | 6.3 ± 3.0                             | ...                       | 0.04 ± 0.02 | ...                                | 19, 11, 12  |
| NGC 2903      | 4.9                              | 1.5 ± 1.0                             | ...                       | 0.07 ± 0.03 | ...                                | 19, 11, 12  |
| NGC 3351      | 5.8                              | <4.0                                  | ...                       | 0.15 ± 0.07 | <9.7                               | 19, 11, 20, 12 |
| NGC 3368      | 8.9                              | <8.8                                  | ...                       | 0.32 ± 0.05 | 7.7_{2.5}^{7.7}                   | 19, 11, 21, 5 |
| NGC 4220      | 6.1                              | 1.6 ± 1.3                             | ...                       | 0.12 ± 0.06 | ...                                | 19, 11, 12  |
| NGC 4258      | 7.6                              | <4.3                                  | ...                       | 0.12 ± 0.03^a | 37.8 ± 0.4                        | 19, 11, 22, 5 |
| M101          | 5.9                              | <0.7                                  | ...                       | 0.05 ± 0.03 | <3                                 | 19, 11, 12, 22 |

Note. Stellar masses are assumed to have an uncertainty of 0.15 dex.

^a Galaxies with dominant classical bulges.

References. (1) Licquia & Newman (2015), (2) Bland-Hawthorn & Gerhard (2016), (3) Sesar et al. (2011), (4) Xue et al. (2015), (5) Kormendy & Ho (2013), (6) Sick et al. (2015), (7) Ibata et al. (2014), (8) Monachesi et al. (2016a), (9) Gilbert et al. (2014), (10) Tamm et al. (2012), (11) Harmsen et al. (2017), (12) Salo et al. (2015), (13) Rodríguez-Rico et al. (2006), (14) Schechtman-Rook & Bershady (2013), (15) Schechtman-Rook & Bershady (2014), (16) Rejkuba et al. (2014), (17) Peacock et al. (2015), (18) Trujillo & Filiñi (2016), (19) Merritt et al. (2016), (20) Sarzi et al. (2002), (21) Möllerhoff & Heidt (2001), (22) Kormendy et al. (2010).
coef-fi-cients consistent with being drawn from uncorrelated data sets at least 15% of the time.

There are six “classical” bulges in our sample, shown in black, all but one (NGC 4258) with masses in excess of $2 \times 10^{10} M_{\odot}$—these could plausibly have been expected to have been formed in (minor or major) mergers (e.g., Kormendy & Kennicutt 2004). Three galaxies with classical bulges (M31, NGC 3115, Cen A) indeed have massive metal-rich stellar halos—carrying >20% of the total galaxy stellar mass—indicative of a minor or major merger. Three (M81, NGC 4258, NGC 7814) have less massive stellar halos. NGC 4258 has a low-mass classical bulge and a relatively uninformative limit on its stellar halo mass. NGC 7814 has a very large bulge five times more massive than its stellar halo. Most notable among these is M81, with a large classical bulge and an anemic stellar halo containing only 2 ± 0.9% of its total stellar mass. M81 shows no sign of any significant past major or minor merging activity that was expected to drive the formation of its classical bulge.

4. Discussion and Conclusions

MW peer galaxies have a wide range in stellar halo masses and therefore merger histories that appear not to correlate significantly with bulge-to-total ratio, bulge mass, or BH mass. This appears to pose a challenge for models where galaxy bulges (even just classical bulges) are formed primarily by minor or major merging activity.

A detailed comparison with hydrodynamical models is desirable but beyond the scope of this Letter. A principled and informative comparison would have high enough resolution to model bulge growth and stellar feedback realistically in the main and satellite galaxies, a large enough dynamic range and sample size to model a range of merger histories and halo masses, and include an effort to connect observational and simulated metrics fairly. Such simulations are coming online soon and should shed light on this issue.

In the meantime, qualitative insight can be gained by comparing with trends predicted by simplified models incorporating a wide range of binary mergers. Hopkins et al. (2010) expects $B/T \sim M_{\text{secondary}}/M_{\text{primary}}$ for star-dominated progenitors; such a trend is qualitatively illustrated in the center of the left panel of Figure 2 by assuming $M_{\text{stellar halo}} \sim M_{\text{secondary}}$, giving $M_{\text{bulge}} \sim M_{\text{stellar halo}}$. The observations do not follow such a trend. Interestingly, observed bulges are more massive (sometimes by more than an order of
magnitude) than their stellar halos, implying substantial growth of bulges not directly connected to mergers with star-rich satellites.

Much remains to be learned about the use of stellar halo masses and metallicities as metrics of merger history. While relatively late star-rich mergers inevitably leave debris at large masses and metallicities as metrics of merger history. While of bulges not directly connected to mergers with star-rich of stellar halo signature.

Of our results.

1. A wide range of (quieter) merger histories, giving an order of magnitude range in stellar halo masses from \( \sim 3 \times 10^9 M_\odot \) to \( \sim 3 \times 10^6 M_\odot \), result in galaxies with small bulges with "pseudobulge"-like properties (highlighted in red in Figures 1–3). Low-mass bulge formation mechanisms that do not require intense merging activity (such as secular evolution, disk instabilities, or misaligned gas accretion) appear at first sight to be consistent with our observations for these galaxies.

2. Similarly, a wide range of merger histories can give rise to massive, "classical" bulges with massive central BHs (denoted in black in Figures 1–3). Three out of five local galaxies (M31, NGC 3415, and Cen A) with massive classical bulges have massive stellar halos \( M_{\text{halo}} > 2 \times 10^{10} M_\odot \), consistent with (but not requiring) a star-rich minor or major merger origin. The other galaxies with massive classical bulges appear to have lower-mass stellar halos implying a quieter accretion history. These galaxies—exemplified most vividly by M81—may be ideal laboratories to study massive bulge formation through pathways such as early gas-rich accretion, violent disk instabilities, or misaligned infall of gas throughout cosmic time.

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