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Structure and Evolution of Dwarf Galaxies

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Abstract. Different structural parameter correlations show how classical bulge components and elliptical galaxies are different from spiral and S0 galaxy disks, irregular (Im) galaxies, and spheroidal (Sph) galaxies. In contrast, the latter, apparently diverse galaxies or galaxy components have almost identical parameter correlations. This shows that they are related. A review of galaxy transformation processes suggests that S0 and spheroidal galaxies are star-formation-quenched, “red and dead” versions of spiral and Im galaxies. In particular, Sph galaxies are bulgeless S0s. This motivates a parallel sequence galaxy classification in which an S0a–S0b–S0c–Sph sequence of decreasing bulge-to-total ratios is juxtaposed to an Sa–Sb–Sc–Im sequence of star-forming galaxies. All parameter sequences show a complete continuity from giant galaxies to the tiniest dwarfs. Dwarfs are not a new or different class of galaxies. Rather, they are the extreme products of transformation processes that get more important as gravitational potential wells get more shallow. Smaller Sph and S+Im galaxies have lower stellar densities because they retain fewer baryons. Comparison of the baryonic parameter correlations with those for dark matter halos allows us to estimate baryon loss as a function of galaxy mass. Extreme dwarfs are almost completely dominated by dark matter.

1 A Parallel Sequence Galaxy Classification

This paper combines visible-galaxy scaling relations from Kormendy & Bender (2012) with dark matter scaling relations from Kormendy & Freeman (2014). Results on visible galaxies are conveniently encoded in a parallel sequence galaxy classification scheme shown in Fig. 1.

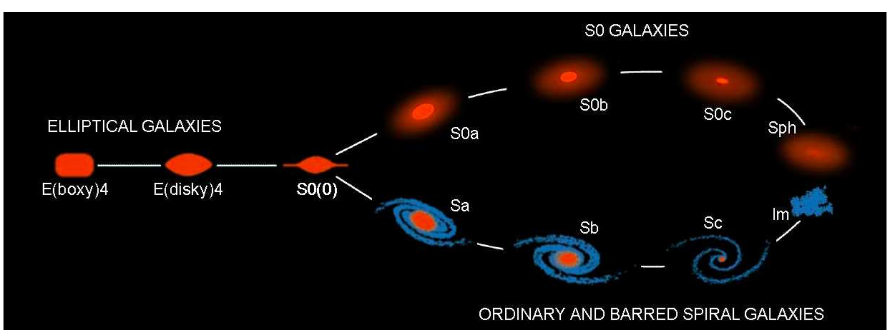

Fig. 1 Parallel sequence galaxy classification including spheroidal (Sph) galaxies as bulgeless S0 galaxies juxtaposed with irregular (Im) galaxies. From Kormendy & Bender (2012).

This updates a parallel sequence classification proposed by van den Bergh (1976). Kormendy & Bender add Sph galaxies as S0s that have no bulge component. This is motivated by the observation that S0 galaxies have bulge-to-total luminosity ratios that range from almost 1 to almost 0 (see also Laurikainen et al. 2010). Kormendy & Bender find a continuous transition in properties – including density profiles but also kinematic properties – between S0 disks and spheroidal galaxies. Figure 2 shows the parameter correlations that illustrate this continuity. S0-like galaxies are given a diffferent name when they have no bulges: They are called Sphs.

Cappellari et al. (2011) and Krajnović et al. (2011) propose a similar parallel sequence classification (without Sphs).

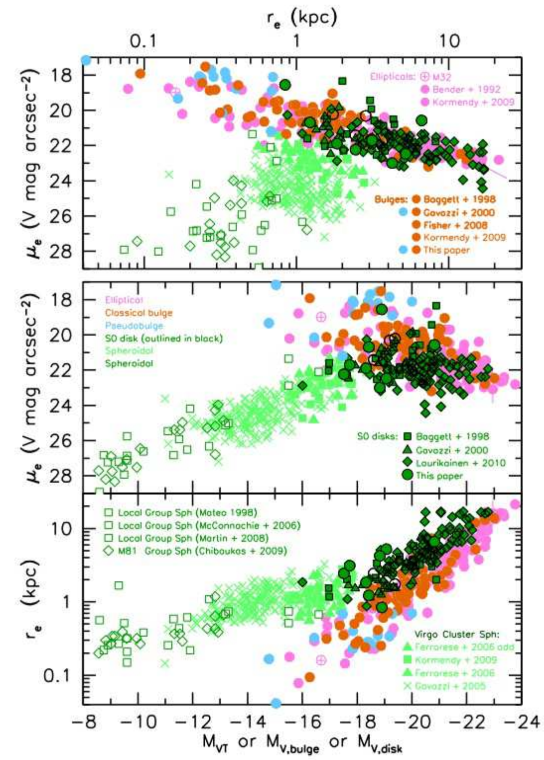

Fig. 2 Parameter correlations for ellipticals, bulges, Sph galaxies, and S0 disks. Bulges and disks of S0s are plotted separately. Plotted parameters are the major-axis effective radius r_e that encloses half of the light of the galaxy component, the effective brightness μ_e at r_e, and the total V-band absolute magnitude of the galaxy or galaxy component. The middle panel shows the Freeman (1970) result that disks of giant galaxies tend to have the same central surface brightness μ_0. Here, $\mu_e \simeq 22.0$ V mag arcsec^{-2} corresponds (for an exponential) to $\mu_0 = \mu_e - 1.82 \simeq 20.2$ V mag arcsec$^{-2} \simeq 21$ B mag arcsec^{-2}, brighter than Freeman's value 21.65 B mag arcsec^{-2} because μ_e is not corrected to face-on orientation. From Kormendy & Bender (2012), who conclude: (1) Sphs are continuous with the disks of S0 galaxies. (2) The kink in the μ_e – M_V relation at $M_V \sim -18$, where bulges disappear in Fig. 4, marks the transition to a baryon retention sequence: tinier dwarf galaxies retain fewer baryons (Fig. 6). Continuity between Sphs and S0 disks is one reason why Fig. 1 shows spheroidal galaxies as bulgeless S0s. Note that Sphs overlap in M_V with but are distinct from bulges and elliptical galaxies. They are not "dwarf ellipticals;" they are related to disks (Kormendy 1985, 1987).

2 S0+Sph Galaxies as Transformed Spiral+Irregular Galaxies

The observational result that motivates the conclusions in this paper is illustrated in Figure 3: Samples now of hundreds of galaxies show: *The continuous parameter sequence defined by Sphs and by the disks (but not bulges) of S0 galaxies is indistinguishable from the parameter sequence defined by Magellanic irregular (Im) galaxies and by the disks (but not bulges) of spiral galaxies.* This result was first found for dwarf galaxies by Kormendy (1985, 1987). Kormendy & Bender (2012) extend it to the highest-luminosity S and S0 disks.

The most robust conclusion is that Sph galaxies +S0 disks are related to Im galaxies + S galaxy disks. Both together are fundamentally different from classical bulges and ellipticals. This conclusion is also based on additional results that are not included in structural parameter correlations; one is that S+S0 disks are flat, whereas bulges+ellipticals are essentially three-dimensional. Understanding the above similarities and differences requires interpretation, but that interpretation now seems comfortably secure: (1) *Bulges+elliptical galaxies form via major mergers, whereas disks+Im+Sph galaxies form by cold gas accretion.* And more directly from Figure 3: (2) *Sphs+S0 disks are transformed – i. e., star-formation-quenched – "red and dead" versions of Im galaxies + S galaxy disks.*

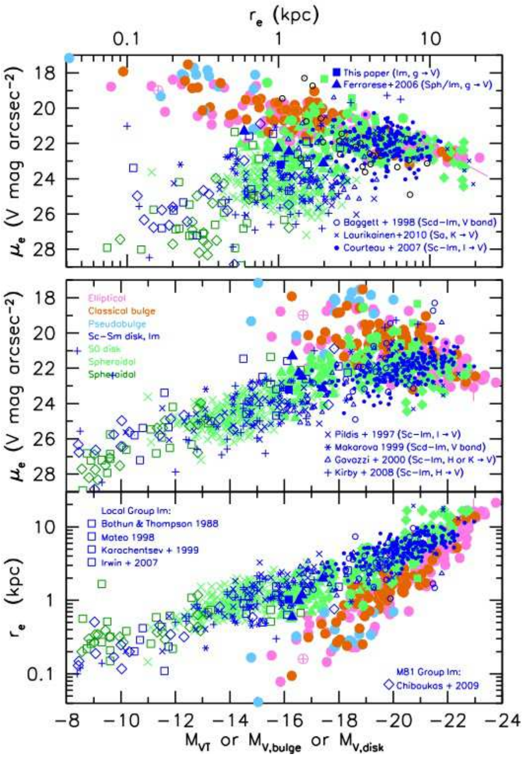

Fig. 3 Figure 2 parameter correlations with disks of Sa – Im galaxies added as blue points. When bulge-disk decomposition is necessary, the two components are plotted separately. Disks are not corrected to face-on orientation. The blue points represent 407 galaxes from 14 sources listed in the keys. From Kormendy & Bender (2012): They conclude that structural parameter correlations for Sa – Im galaxy "disks" are almost identical to those for S0 – Sph "disks". This confirms conclusions in Kormendy (1985, 1987) using a large galaxy sample.

3 S+Im → S0+Sph Galaxy Transformation Processes

Kormendy & Bender (2012) provide an ARA&A-style review of physical processes that heat galaxy disks and that use up or remove gas and so quench star formation. They suggest that the following processes all are important in transforming Im + S disks into Sph + S0 disks:

1. *Internal process:* Dekel & Silk (1986; see also Larson 1974; Saito 1979) "suggest that *both the dIs and the [dSphs] have lost most of their mass* in winds after the first burst of star formation, and that this process determined their final structural relations. The dIs somehow managed to retain a small fraction of their original gas, while the [dSphs] either have lost all of their gas at the first burst of star formation or passed through a dI stage before they lost the rest of the gas and turned [dSph]." Kormendy and Bender conclude that *"the Sph + Im sequence of decreasing surface brightness with decreasing galaxy luminosity is a sequence of decreasing baryon retention"* (emphasis in both originals).

   Figure 2 shows that surface brightnesses in the Sph +S0 sequence start to decrease at $M_{V,\rm disk} \simeq -18$, just where bulges disappear and where we therefore change galaxy classifications from S0 to Sph (i. e., where plot symbols change from dark to light green). Figure 4 independently finds the S0→Sph transition from rotation curve decompositions. As dark matter $V_{\rm circ}$ decreases, bulges decrease in importance relative to disks until they disappear at $V_{\rm circ} \simeq 104 \pm 16$ km s^{-1}. The Tully-Fisher (1976) relation shows that this corresponds to $M_V \simeq -19$ for spirals (Courteau et al. 2007) and $M_V \simeq -18$ for S0s (Bedregal et al. 2006). It is probably not an accident that baryons start to be lost roughly where bulges stop to contribute to the gravitational potential.

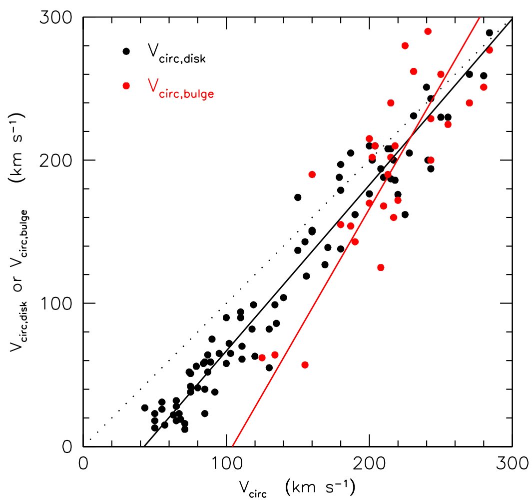

Fig. 4 Maximum rotation velocity of bulge ($V_{\rm circ,bulge}$: *red points*) and disk $V_{\rm circ,disk}$ (*black points*) components given in bulge-disk-halo decompositions of observed rotation curves $V(r)$ whose outer, dark matter rotation velocities are $V_{\rm circ}$ (Kormendy & Freeman 2014; references to the $V(r)$ decomposition papers are given there). The dotted line indicates that rotation velocities of the visible and dark matter are equal. Every red point has a corresponding black point, but many late-type galaxies are bulgeless, and then the plot shows only a black point. The lines are symmetric least-squares fits; the disk fit is $V_{\rm circ,disk} = (1.16 \pm 0.03)(V_{\rm circ} - 200) + (183 \pm 3)$ km s^{-1}; $V_{\rm circ,bulge} = (1.73 \pm 0.29)(V_{\rm circ} - 200) + (166 \pm 9)$ km s^{-1} is the bulge fit. The bulge correlation is steeper than the disk correlation. Bulges disappear at $V_{\rm circ} \simeq 104 \pm 16$ km s^{-1}.

1. (*Continued*) The transition in Figures 2 and 3 to (I suggest) a baryon retention sequence in smaller dwarfs corresponds within errors to the transition in edge-on galaxies from giants that do to dwarfs that do not have well-defined dust lanes in their disk midplanes (Dalcanton et al. 2004). They argue that the transition is not caused by changes in gas density. Rather, they argue that it is caused by a transition in giant galaxies to a regime in which disk instability leads to lower gas turbulence, smaller gas scale heights, and enhanced star formation. It is plausible that star formation is less efficient in smaller dwarfs. However: *The observation that dwarf Im and Sph galaxies show the same decrease in surface brightness with decreasing luminosity shows that the dominant effect is not one that depends on the presence of gas. This favors the suggestion that the $\mu_e(M_V)$ relation in Figures 2 and 3 is a baryon retention sequence at $M_V > -18$.* See also Figure 6.

   It may be surprising that Sph+S0 and Im+S galaxies have similar surface brightnesses, because the latter are star-forming and so presumably have smaller mass-to-light ratios. However, (1) at high luminosities, internal absorption partly compensates for smaller mass-to-light ratios, and (2) at low luminosities, star formation in Im galaxies is gentle. Nevertheless, it is fair to emphasize that more work is needed to understand the detailed engineering that results in Sph+S0 and Im+S correlations that look so nearly identical.

2. *Environmental processes I:* Ram-pressure stripping – long underestimated in importance – is now An Idea Whose Time Has Come. Gunn & Gott (1972) suggested, based on the detection of X-ray-emitting, hot gas in the Coma cluster (Meekins et al. 1971; Gursky et al. 1971) that "*a typical galaxy moving in it will be stripped of its interstellar material.* We expect *no normal spirals* in the central regions of clusters like Coma. The lack of such systems is, of course, observed" (emphasis in the original). Calculations persuaded some people to neglect ram-pressure stripping even while many observations provided indirect evidence for its importance. Spirals near the center of the Virgo cluster are deficient in H I gas (Cayette et al. 1990, 1994; Chung et al. 2009). Also, Faber & Lin (1983); Lin & Faber (1983); Kormendy (1987), van den Bergh (1994b), and Kormendy et al. (2009, hereafter KFCB) suggested that Sph galaxies are ram-pressure-stripped dS+Im galaxies, based in part on observations (Einasto et al. 1974; van den Bergh 1994a, 1994b; Mateo 1998) that – with a few (understandable) exceptions – close dwarf companions of Local Group giant galaxies are almost all spheroidals, that distant companions are irregulars, and that galaxies with intermediate (Sph/Im) morphologies live at intermediate distances. Ever since van den Bergh (1976), these ideas provided the interpretation of a parallel sequence classification (Figure 1 here) that was constructed operationally to encode the full range of S0+Sph bulge-to-total luminosity ratios B/T from almost 1 to exactly 0.

   Spectacular observations of ram-pressure stripping in action now clearly demonstrate the importance of this process (see Sun et al. 2010; Kormendy & Bender 2012 for reviews). Kenney et al. (2004, 2008), Oosterloo & van Gorkom 2005, and Chung et al. (2007, 2009) find that many spiral galaxies near the center of the Virgo cluster show long Hα or H I tails interpreted to be cold gas that is being stripped by the ambient X-ray-emitting gas (Böhringer et al. 1994). Kormendy and Bender emphasize that these galaxies and the H I - depleted galaxies are substantially brighter than almost all Sphs: "If even the deep gravitational potential wells of still-spiral galaxies suffer H I stripping, then the shallow potential wells of dS + Im galaxies are more likely to be stripped." The most impressive recent example of ram-pressure stripping is the multi-wavelength (CO gas+H II+X-ray) tail of the galaxy ESO 137-001 in Abell 3627 (Sun et al. 2006, 2007, 2010; Woudt et al. 2008; Sivanandam et al. 2010; Pavel et al. 2014; Figure 5 here).

   For a recent treatment of ram-pressure stripping in the Galactic halo, see Gatto et al. (2013).

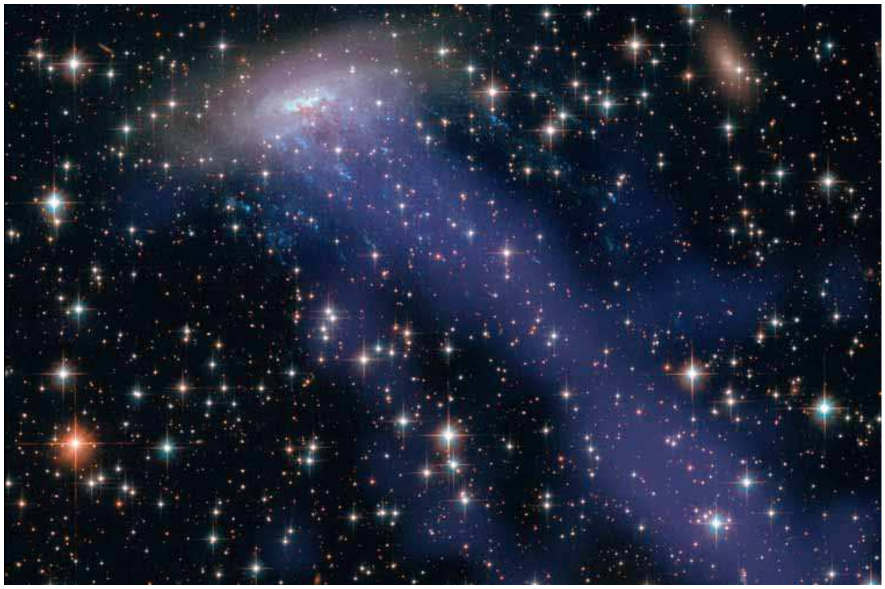

Fig. 5 Composite *Hubble Space Telescope* (HST) and *Chandra X-Ray Observatory* image of galaxy ESO 137-001 in Abell 3627. The HST image is a *I*-, *g*-, and *U*-band color composite. Added in blue is the X-ray image; it extends the lighter blue optical streaks of ongoing star formation toward the lower-right. This material is interpreted to be ram-pressure stripped. The image source is `http://www.spacetelescope.org/images/heic1404b/` and `http://apod.nasa.gov/apod/ap140328.html.` At a distance of ~ 64 Mpc, the absolute magnitude of ESO 137-001 is $M_V \sim -20.8$. Conveniently, this field of view also shows a normal-looking Sph galaxy at upper-right; it is ~ 3 mag fainter than ESO 137-001. Again, if we see a giant galaxy caught in the process of undergoing ram-pressure stripping, it is not surprising that a much smaller Sph galaxy is thoroughly "red and dead."

3. *Environmental processes II:* Dynamical harassment results from many, high-speed encounters with other galaxies in a cluster and with the overall cluster potential. Simulations show that (1) it promotes gas flow toward galaxy centers, (2) it heats disks, especially vertically, and (3) it strips off the outer parts of galaxies (Moore et al. 1996, 1998, 1999; Lake et al. 1998). Even in poor environments like the Local Group, tidal stirring of dwarfs on elliptical orbits around the Galaxy or M 31 should have similar effects (Mayer et al. 2001a, b, 2006). One success of this picture is that inflowing gas can feed star formation and help to explain why spheroidals, in which star formation stopped long ago, do not have lower surface brightnesses than current versions of S+Im progenitors (Figure 3). This process is clean and inescapable.

   Kormendy & Bender (2012) conclude that *dynamical harassment is much more important in the Virgo cluster than we thought.* Edge-on S0s with close companions show warps in their outer disks that will phase-wrap around the center into structures that resemble Sphs in their shapes and density profiles (NGC 4762 and NGC 4452; their Figures 4 and 8, respectively). They identify S0/Sph transition objects: (1) NGC 4638 is an edge-on S0 with a Gaussian (i. e., radially truncated) inner disk embedded in a boxy, E3 halo that has the properties of a large Sph (their Figures 13 – 16). (2) VCC 2048 is an E6 Sph with an embedded edge-on, S0 disk (their Figures 10 – 12). Indeed, many Virgo S0s have Gaussian disk profiles. Most telling is the observation that several Virgo cluster S0s have bars embedded in steep-, often Gaussian-profile lenses with no sign of a disk outside the bar (NGC 4340, NGC 4442, and NGC 4483, their § A.12). We do not know how to form a bar that fills the whole disk, because an outer disk is generally required as an angular momentum sink to allow a bar to grow. Kormendy and Bender suggest that the outer disks in these galaxies have been heated or stripped off. Finally, they interpret the “new class of dwarfs that are of huge size and very low surface brightness” (Sandage & Binggeli 1984) as “spheroidals that have been harassed almost to death.”

4. *Environmental processes III:* Starvation of late growth by cold-gas infall (Larson et al. 1980) seems inevitable in environments like the center of the Virgo cluster where the ambient gas is very hot. Even in environments like the Local Group, Sph galaxies that orbit around the Galaxy and M 31 at velocities $V \sim 200$ km s^{-1} are unlikely to encounter cold gas slowly enough to be able to accrete it. And much of the gas in the Local Group may in any case be in a warm-hot intergalactic medium (WHIM: Davé et al. 2001).

So Kormendy & Bender (2012) “suggest that the relevant question is not ‘Which of these mechanisms is correct?’ It is ‘How can you stop any of them from happening?’ It seems likely that all of the above processes matter.” Engineering details probably depend on environment.

4 Visible Matter and Dark Matter Parameter Correlations

Figure 6 illustrates our conclusion that, at $M_V \gtrsim -18$, the dwarf spiral, Im, and Sph galaxies in earlier figures form a sequence of decreasing baryon retention in smaller galaxies (KFCB; Kormendy & Bender 2012; Kormendy & Freeman 2014). In contrast, bulges and ellipticals

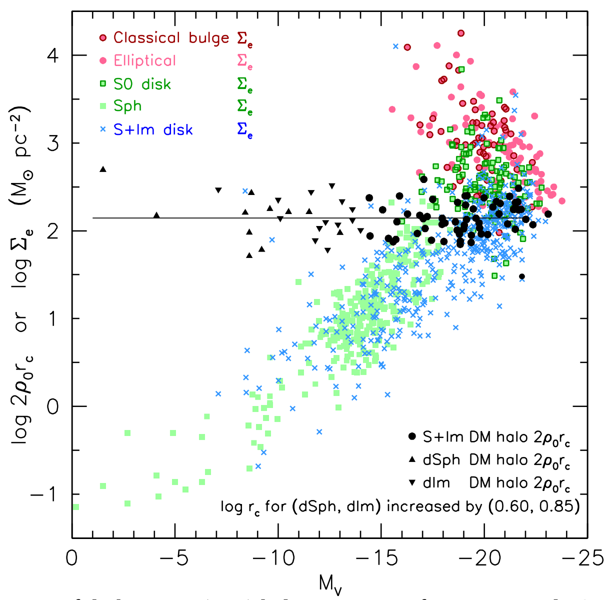

Fig. 6 Comparison of dark matter (DM) halo parameters from Kormendy & Freeman (2014) with visible matter parameters from Kormendy & Bender (2012). DM parameters are from maximum-disk rotation curve decompositions (*black circles*) or from cored isothermal halo models applied to the dispersion profiles of dSph galaxies (*black triangles*) or to the $V \propto r$ rotation curves and velocity dispersions of H I in dIm galaxies (*upside-down black triangles*) (see Kormendy & Freeman 2014, the source of this figure). Central projected densities are plotted for DM halos; effective surface densities $\Sigma_e = \Sigma(r_e)$ are shown for visible components. Here r_e is the radius that contains half of the light of the component. Surface brightnesses are converted to stellar surface densities using mass-to-light ratios $M/L_V = 8$ for ellipticals, 5 for classical bulges and S0 disks, and 2 for spiral galaxy disks, Im galaxies, and Sph galaxies.

together form a sequence of increasing dissipation during the formation of smaller galaxies. For $M_V < -18$ galaxies of all kinds, effective densities in stars are similar to DM densities at and interior to the same radius. For Sc–Im systems, this is by construction a consequence (1) of using maximum-disk decompositions and (2) of the "rotation curve conspiracy" (van Albada & Sancisi 1986), i. e., the observation that rotation curves of giant galaxies are roughly flat and featureless, so the parts of galaxies that are controlled by dark matter are not easily distinguished from the parts that are controlled by visible matter or even the parts that are controlled by different components in the visible matter (Figure 4). Caveat: for bulges and ellipticals, high baryon densities at $r \ll r_e$ may pull on DM halos enough to increase their central densities over the values for Sc – Im galaxies that are shown in Figure 6. But bulges and ellipticals have *central* projected densities that are more than 3 dex higher than the effective densities shown in Figure 6. So the central parts of early-type galaxies are *very* baryon-dominated. Even the central densities of disks are 0.7 dex (for an exponential) higher than the effective densities shown in Fig. 6. So even pure disks are moderately dominated by visible matter near their centers. Both results are qualitatively as expected: Visible matter needs to dissipate, sink inside the DM, and become self-gravitating enough to form stars and visible galaxies. And a great deal of dissipation happens in the wet mergers that make normal ellipticals (KFCB): their densities rise above DM densities by larger amounts at fainter M_V.

The important point here is this: At $M_V > -18$, tinier dwarfs are more DM dominated, until by $M_V \gtrsim -10$, they are essentially dark galaxies with just enough of a frosting of stars so that they can be detected. I emphasize two important points: (1) The differences between dIm and dSph galaxies in all parameter correlations shown in this paper are small. Whether or not a galaxy retains cold gas and can still form stars in today's Universe is a second-order effect. This argues – as Dekel & Silk (1986) already emphasized – that the primary effect that engineers the parameter correlations is supernova-driven baryon blowout or another process (such as a failure to capture baryons before cosmic reionization) that has the same effect. (2) Kormendy & Freeman (2014) suggest that there exists a large population of tiny halos that are essentially completely dark and that the discoverable galaxies at $M_V \gtrsim -13$ represent a smaller and smaller fraction of tinier DM halos. This has been suggested as the solution to the problem that the fluctuation spectrum of cold dark matter predicts more dwarfs than are observed in environments like the Local Group (e. g., Moore et al. 1999; Klypin et al. 1999).

5 Conclusions

Kormendy & Bender (2012) propose a parallel sequence galaxy classification (Figure 1 here) in which Sph galaxies appear as bulgeless S0s juxtaposed with Im galaxies. In reality, their progenitors can include late-type spirals, but the Fig. 1 tuning fork is designed for simplicity. S0+Sph galaxies are suggested to be star-formation-quenched descendants of S+Im galaxies. It seems essentially guaranteed that all transformation processes discussed in §3 are important. Moreover, although there is good agreement between structural parameter correlations for (1) present-day Sphs+S0 disks and (2) present-day Im+S disks, it is of course not guaranteed that the progenitors of Sph and S0 galaxies were exactly like present-day late-type galaxies. The latter are, after all, survivors. The reasons can partly involve stochastic evolution, but they may also involve differences in internal structure and/or environment.

These ideas are slowly gaining acceptance. An observationally biased but still incomplete list of papers includes Grebel et al. (2003); van Zee et al. (2004); Mayer et al. (2006); Boselli et al. (2008a, b); Tolstoy et al. (2009); Ryś et al. (2013, 2014); and Janz et al. (2013). KFCB and Kormendy & Bender (2012) address remaining controversies.

From the perspective of this conference, the important – and robust! – conclusion is this:

Dwarf spiral, irregular, and spheroidal galaxies are not new and special kinds of galaxies, as has often been suggested. Rather: *There is a complete continuity in structural parameter scaling relations* (Figures 2 – 4 and 6), *kinematics and dynamics, star formation properties, and metallicity distributions between the disks of giant galaxies and all three subsets of dwarf galaxies. Fainter than* $M_V \sim -18$, *the properties of galaxies change as their gravitational potential wells get more shallow; this is qualitatively consistent with the increased importance at lower masses of internal and environmental transformation processes. Also, many aspects of galaxy evolution get more stochastic in smaller galaxies. For example, star formation gets more bursty. Many quantitative details remain to be worked out. But this is engineering. A big-picture view of the evolution of dwarf galaxies seems comfortably in place:*

All forms of violence – including supernova energy feedback, dynamical harassment, and external ram-pressure stripping – get more important for smaller galaxies. The main result is that smaller galaxies lose more of their baryons or never acquire them. Smaller dwarfs are more dominated by dark matter. Whether or not they retain enough cold gas to feed some star formation is very much a second-order effect. Baryon loss at low halo masses may be so severe that we discover only a small fraction of the smallest, essentially dark halos. This can reconcile the observed scarcity of dwarf galaxies in field environments with our expectations of large numbers of dwarfs that are predicted by the cold dark matter fluctuation spectrum.

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7 References

Bedregal, A. G., Aragón-Salamanca, A., & Merrifield, M. R. 2006, MNRAS, 373, 1125
Böhringer, H., et al. 1994, Nature, 368, 828
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008a, ApJ, 674, 742
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008b, A&A, 489, 1015
Cappellari, M., et al. 2011, MNRAS, 416, 1680
Cayette, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, AJ, 107, 1003
Cayette, V., van Gorkom, J. H., Balkowski, C., & Kotanyi, C. 1990, AJ, 100, 604
Chung, A., van Gorkom, J. H., Kenney, J. D. P., Crowl, H., & Vollmer, B. 2009, AJ, 138, 1741
Chung, A., van Gorkom, J. H., Kenney, J. D. P., & Vollmer, B. 2007, ApJ, 659, L115
Courteau, S., et al. 2007, ApJ, 671, 203
Dalcanton, J. J., Yoachim, P., & Bernstein, R. A. 2004, ApJ, 608, 189
Davé, R., et al. 2001, ApJ, 552, 473
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Einasto, J., Saar, E., Kaasik, A., & Chernin, A. D. 1974, Nature, 252, 111
Faber, S. M., & Lin, D. N. C. 1983, ApJ, 266, L17
Freeman, K. C. 1970, ApJ, 160, 811

Gatto, A., et al. 2013, MNRAS, 433, 2749
Grebel, E. K., Gallagher, J. S., & Harbeck, D. 2003, AJ, 125, 1926
Gunn, J. E., & Gott, J. R. 1972, ApJ, 176, 1
Gursky, H., et al. 1971, ApJ, 167, L81
Janz, J., et al. 2013, arXiv:1308.6496
Kenney, J. D. P., Tal, T., Crowl, H. H., Feldmeier, J., & Jacoby, G. H. 2008, ApJ, 687, L69
Kenney, J. D. P., van Gorkom, J. H., & Vollmer, B. 2004, AJ, 127, 3361
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Kormendy, J. 1985, ApJ, 295, 73
Kormendy, J. 1987, in Nearly Normal Galaxies: From the Planck Time to the Present, ed. S. M. Faber (New York: Springer), 163
Kormendy, J., & Bender, R. 2012, ApJS, 198, 2 (They list references in the keys of Figures 2 and 3.)
Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, ApJS, 182, 216 (KFCB)
Kormendy, J., & Freeman, K. C. 2014, ApJ, in preparation
Krajnović, D., et al. 2011, MNRAS, 414, 2923
Lake, G., Katz, N., & Moore, B. 1998, ApJ, 495, 152
Larson, R. B. 1974, MNRAS, 169, 229
Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692
Laurikainen E., Salo H., Buta R., Knapen J. H., & Comerón S., 2010, MNRAS, 405, 1089
Lin, D. N. C., & Faber, S. M. 1983, ApJ, 266, L21
Mateo, M. 1998, ARA&A, 36, 435
Mayer, L., Mastropietro, C., Wadsley, J., Stadel, J., & Moore, B. 2006, MNRAS, 369, 1021
Mayer, L., et al. 2001a, ApJ, 547, L123
Mayer, L., et al. 2001b, ApJ, 559, 754
Meekins, J. F., Fritz, G., Chubb, T. A., Friedman, H., & Henry, R. C. 1971, Nature, 231, 107
Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A. 1996, Nature, 379, 613
Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139
Moore, B., et al. 1999, ApJ, 524, L19
Oosterloo, T., & van Gorkom, J. 2005, A&A, 437, L19
Pavel, J., Combes, F., Cortese, L., Sun, M., & Kenney, J. D. P. 2014, arXiv:1403.2328
Ryś, A., Falcón-Barroso, J., & van de Ven, G. 2013, MNRAS, 428, 2980
Ryś, A., van de Ven, G., & Falcón-Barroso, J. 2014, MNRAS, 439, 284
Saito, M. 1979, PASJ, 31, 193
Sandage, A., & Binggeli, B. 1984, AJ, 89, 919
Sivanandam, S., Rieke, M. J., & Rieke, G. H. 2010, ApJ, 717, 147
Sun, M., Donahue, M., & Voit, G. M. 2007, ApJ, 671, 190
Sun, M., et al. 2006, ApJ, 637, L81
Sun, M., et al. 2010, ApJ, 708, 946
Tolstoy, E., Hill, V., & Tosi, M. 2009, ARA&A, 47, 371
Tully, R. B., & Fisher, J. R. 1977, A&A, 54, 661
van Albada, T. S. & Sancisi, R. 1986, Phil. Trans. R. Soc. London A, 320, 447
van den Bergh, S. 1976, ApJ, 206, 883
van den Bergh, S. 1994a, AJ, 107, 1328
van den Bergh, S. 1994b, ApJ, 428, 617
van Zee, L., Skillman, E. D., & Haynes, M. P. 2004, AJ, 128, 121
Woudt, P. A., Kraan-Korteweg, R. C., Lucey, J., Fairall, A. P., & Moore, S. A. W. 2008, MNRAS, 383, 445