

Scaling laws in disk galaxies

Alister W. Graham¹

¹Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia.

Abstract. A brief overview of several recent disk galaxy scaling relations is presented, along with some historical background. In particular, after introducing the (basic) radial light profiles of disk galaxies, I explain several important ‘structural’ scaling relations and review the latest bulge-(black hole mass) diagrams. I go on to present the typical bulge-to-disk flux ratios of disk galaxies and suggest the use of a grid of bulge-to-disk ratio versus disk Hubble type — based on the nature of the spiral arms — to complement the Hubble-Jeans sequence. I then briefly mention pure disk galaxies before cautioning on difficulties with identifying pseudobulges built from secular evolution. Finally, I conclude by discussing a likely connection between modern day bulges in disk galaxies and high-redshift ($z \sim 2 \pm 0.5$) compact galaxies which may have since acquired a disk via cold flows and quiescent accretion.

1. Light profiles — the radial concentration of stars

Bulges are centrally-located stellar distributions with a smooth appearance that manifest themselves as an excess, a bulge, relative to the inward extrapolation of their galaxies outer disk light (Wyse et al. 1997); noting a distinction between obvious bars, nuclear disks and star clusters. The bulk of a disk can be well approximated by the exponential model (Patterson 1940; de Vaucouleurs 1957, 1958; Freeman 1970). In general, they may be comprised of a thick, thin, and super-thin disk (Schechtman-Rook 2013), often display a break and/or truncation at large radii (van der Kruit 1979, 1987; Erwin, Pohlen & Beckman 2008; Hermann 2013), and bars of varying strength appear in some two-thirds of the local disk galaxy population (e.g. Sheth et al. 2013).

Bulges were, for a long time, considered to have $R^{1/4}$ light profiles (e.g. de Vaucouleurs 1958; Kormendy 1977a; Burstein 1979; Kent 1985; Kodaira et al. 1986; Simien & de Vaucouleurs 1986; Baggett et al. 1998; Lilly et al. 1998; etc.). So popular was the belief in this model that it was referred to as the $R^{1/4}$ law. However, de Vaucouleurs (1959) had noted departures in some bulge light profiles from his (1948) $R^{1/4}$ model, and the exponential model was subsequently shown by others to provide better fits for some bulges (e.g. van Houten 1961; Liller 1966; Frankston & Schild 1976; Spinrad et al. 1978). Shaw & Gilmore (1989) and Wainscoat et al. (1989) reiterated that not all bulges are well described with the $R^{1/4}$ model, and Andredakis & Sanders (1994) showed that *many* bulges are in fact better fit with an exponential model. Andredakis, Peletier & Balcells (1995) subsequently revealed the suitability of Sérsic’s (1963, 1968) $R^{1/n}$ model, which could accommodate $R^{1/4}$ profiles, exponential ($n = 1$) profiles, plus everything in between and at either extreme (i.e. $n < 1$ and $n > 4$). Furthermore, building on the work with elliptical galaxies by Caon et al. (1993) and Young

2. A few select disk galaxy scaling relations

2.1. Insight from elliptical galaxies

Although the bulges of disk galaxies are not simply small elliptical galaxies — because their stellar densities are much higher (see Section 6) — they are similar in the sense that the 3-parameter Sérsic model can describe their light profiles. One can use the luminosity (or rather the absolute magnitude $M = -2.5 \log[L]$), central surface brightness and Sérsic index as the three independent variables. From a sample of many elliptical galaxies, Fig. 2 reveals that these parameters follow log-linear relations that unify the dwarf and giant elliptical galaxies across the alleged divide at $M_B = -18$ mag (Graham & Guzmán 2003). However, when one uses the effective half light parameters (Fig. 3), the continuous, unifying relations are curved. The effective half light radius, and associated surface brightness, have always been somewhat arbitrary quantities. For example, we (astronomers) could have used a radius enclosing 25% or 75% of the total light, and these curved relations would look different again. This would not happen if every light profile was actually an $R^{1/4}$ profile. Without this understanding, it had led some to conclude that the dwarf and giant elliptical galaxies must be distinct species due to their apparent, near-orthogonal distribution in diagrams involving the effective parameters. Fig. 3 reveals, for example, how the log-linear $M - \mu_0$ relation (Fig. 2a) maps into the curved $M - \mu_e$ relation due to the difference between μ_0 and μ_e seen in Fig. 1 and described by Eq. 2. It also reveals the highly curved nature of the $\langle \mu \rangle_e - R_e$ distribution. As detailed in Graham (2013), this curve shown in Fig. 3c has been derived from the log-linear relations that unify the faint and bright elliptical galaxies in Fig. 2.

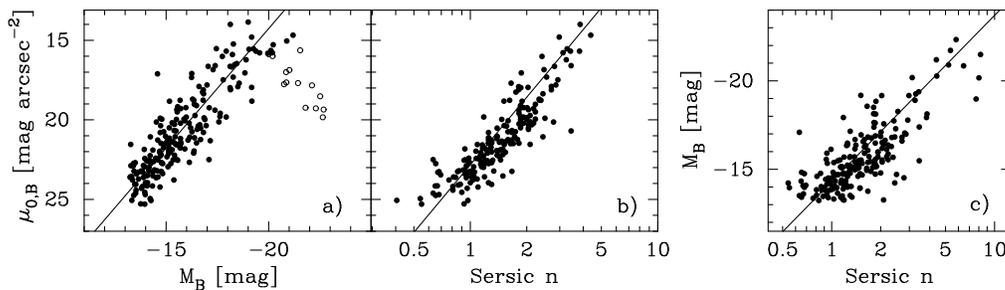


Figure 2. The (B -band) magnitude ($M = -2.5 \log[L]$), central surface brightness (μ_0) and Sérsic index (n) of elliptical galaxies define unifying, continuous, log-linear relations. The deviation at the bright-end of the $\mu_0 - M$ relation in panel a) is due to the presence of partially depleted cores, thought to have formed from the scouring of binary black holes (e.g. Begelman et al. 1980; Faber et al. 1997; Dullo & Graham 2013, and references therein).

2.2. Bulges

We can use the above insight from elliptical galaxies to better understand the bulges of disk galaxies. Just as there is no dichotomy between dwarf elliptical and giant elliptical galaxies at $M_B = -18$ mag, or roughly Sérsic $n = 2$, Fig. 4 reveals no sign of a dichotomy between ‘classical’ $n = 4$ bulges and $n = 1$ (or $n \leq 2$) ‘pseudobulges’. One

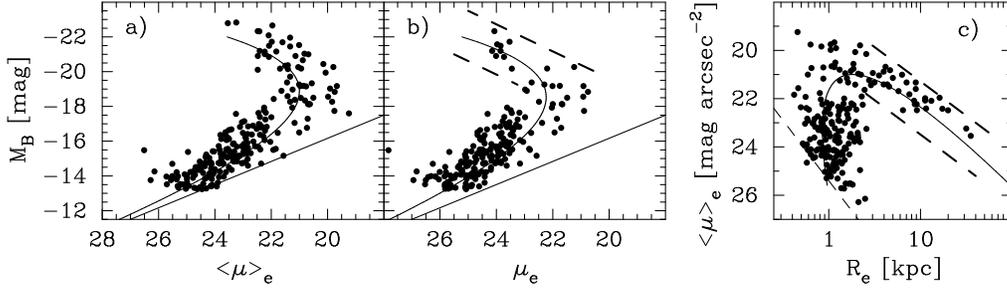


Figure 3. The linear relations from Fig. 2 map into curved relations when ‘effective’ parameters (such as R_e , μ_e or $\langle \mu \rangle_e$) are involved. The bright-arms of these curved relations, marked with the dashed lines, are known as the Kormendy (1977b) relation. Figure adapted from Graham & Guzmán (2003) and Graham (2013).

can also see that, as with the elliptical galaxies, the continuous and linear $M - n$ and $M - \mu_0$ relations for bulges map into a continuous but curved $M - \mu_e$ relation (Fig. 4c).

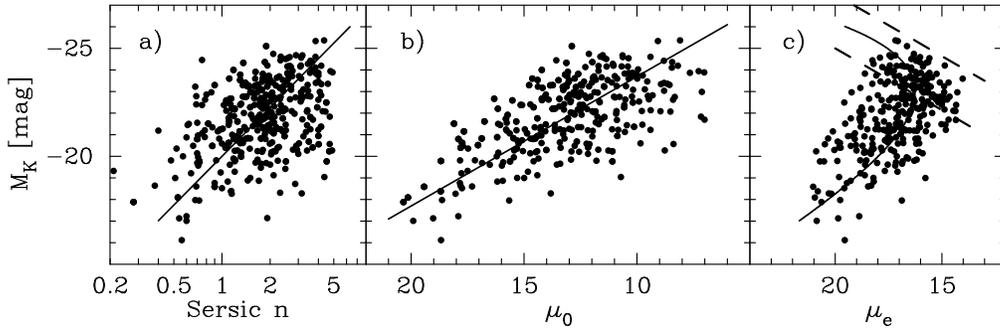


Figure 4. Similar to elliptical galaxies, bulges follow single log-linear scaling relations involving absolute magnitude, central surface brightness and Sérsic index. These two log-linear relations shown in panels a) and b) map into the curved relation shown in panel c), which is not a fit to the data shown there but the requirement / prediction from these two log-linear relations. K -band data has been used here from the compilation in Graham & Worley (2008). The bright arm of the curved (absolute magnitude)-(effective surface brightness) relation for bulges in panel c) is delineated by the dashed lines. Figure adapted from Graham (2013).

Although bulges with $n \lesssim 2$ will ‘appear’ to deviate from those with $n \gtrsim 2$ in the $M - \mu_e$ diagram, the $R_e - \mu_e$ diagram, and also the Fundamental Plane (as noted in Graham & Guzmán 2004, see also Guzmán, Graham & Ismay, in prep.), this is not evidence of a dichotomy but simply reflects that the distribution is curved in diagrams involving effective parameters (see also Graham & Guzmán 2003; Gavazzi et al. 2005; Ferrarese et al. 2006; Côté et al. 2006, 2007).

While rotating bulges with $n \sim 1$ may be a sign of ‘pseudobulges’ grown from the secular evolution of a disk, some care is needed because Domínguez-Tenreiro et al. (1998), Aguerrí et al. (2001) and Scannapieco et al. (2010) have grown bulges with $1 < n < 2$ from minor mergers. Further evidence that a radial light distribution with an exponential profile need not have formed from the secular evolution of a disk are the

existence of both dwarf elliptical galaxies (Young & Currie 1994) and cD galaxy halos (Seigar et al. 2007; Pierini et al. 2008) which have light profiles with $n \approx 1$.

3. Bulge-to-disk flux ratios and the Hubble sequence

The Hubble-Jeans sequence (Jeans 1919, 1928; Hubble 1926, 1936; reviewed in van den Bergh 1997 and Sandage 2004) is not purely a bulge-to-disk (B/D) flux ratio sequence; the pitch angle (e.g., Kennefick 2013; Puerari 2013; Davis 2013) is a primary criteria for determining the Hubble type. Indeed, in the Hubble Atlas of Galaxies, Sandage (1961) made the spiral arms the primary criteria, noting that Sa galaxies can therefore exist with both large and small bulges. There is in fact a range of B/D flux ratios for any given spiral Hubble type (Fig. 5).

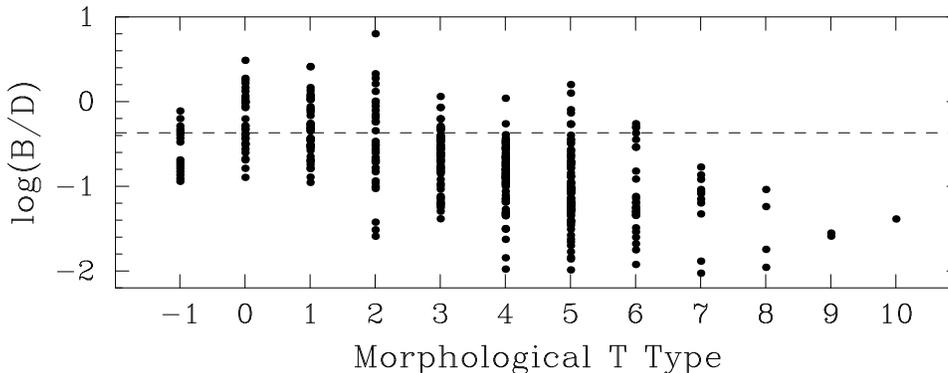


Figure 5. Bulge-to-disk flux ratios. Adapted from Graham & Worley (2008). The dashed line corresponds to a bulge-to-total flux ratio of 0.3, and reveals no evidence for a divide which has been advocated by some as delineating pseudobulges from classical bulges. (Note: T=1=Sa, T=2=Sab, T=3=Sb, T=5=Sc, T=7=Sd, etc.)

The range of B/D flux ratios for the lenticular galaxies had led some to propose an S0 sequence of varying B/D flux ratio, running parallel to the spiral sequence (van den Bergh 1976; Cappellari et al. 2011; Kormendy & Bender 2012), but as Fig. 5 shows, the spiral galaxies actually occupy a grid of pitch angle (i.e. roughly galaxy type: Sa, Sb, Sc, Sd) versus B/D ratio. That is, it is not simply that the S0 galaxies display a range or sequence of B/D values, every disk galaxy type does. It is therefore suggested here that a grid (of spiral type based on the spiral arms, and the bulge-to-disk flux ratio or bulge magnitude) might be a useful ($z = 0$) classification scheme, in addition to the Hubble-Jeans sequence and expanding upon the van den Bergh track of just three parallel sequences, referred to as a comb diagram by Cappellari et al. (2011). That is, while this comb diagram focusses on the bulge-to-disk flux ratio and the prominence of the spiral arms (strong for spirals, non-existent for lenticular galaxies, and of intermediate strength for the anemic spirals), there may also be value in a grid which focusses on the bulge-to-disk flux ratio and the extent to which the spiral arms are unwound.

3.1. Bulgeless galaxies

There is some need for qualification when it comes to the term ‘bulgeless’. The Milky Way has been referred to as a bulgeless galaxy by some who regard it as a pure disk galaxy harboring no ‘classical’ bulge. However, it certainly has a bulge relative to the underlying disk, and Dékány et al. (2013) suggest that it is comprised of both a classical bulge and a pseudobulge. The Scd galaxy NGC 1042 is another example which has recently been heralded as a bulgeless galaxy, and importantly one with an AGN (i.e. a supermassive black hole), but Knapen et al. (2003) have shown that it does actually have a bulge. Similarly, Simmons et al. (2013) call galaxies bulgeless if B/T is small ($< \sim 0.05$), even though a bulge is often still apparent. There is thus some ambiguity as to what is meant by ‘bulgeless’. Having noted this, readers are directed to the references in Secrest et al. (2013) for ‘bulgeless’ galaxies with AGN, some of which may truly be bulgeless.

While IC 5249 has less than 2% of its total light in a bulge component, NGC 300 (Bland-Hawthorn et al. 2005) has no perceivable bulge. There are also examples of apparently bulgeless, super-thin edge-on galaxies (Kautsch 2009), and super-thin disks such as in NGC 891 (see Schechtman-Rook 2013).

4. (Black hole)-bulge scaling relations

Within spiral galaxies, one may ask if the mass of the central black hole scales better with the bulge mass (or bulge-to-disk ratio), or perhaps some other property such as the pitch angle of the spiral arms (e.g. Seigar et al. 2008; Treuthardt et al. 2012; Berrier et al. 2013). If truly bulgeless galaxies do have active galactic nuclei (AGN), then the $M_{\text{bh}}-M_{\text{bulge}}$ mass relation defined by big bulges can not apply for obvious reasons. The existence of spiral patterns in pure disk galaxies (e.g. Valencia-Enriquez & Puerari 2013) at least offers hope for an M_{bh} -(pitch angle) relation in disks with AGN but no bulge. However the possibly transient nature of spiral arms raises the question as to the time scale on which spiral arms may evolve (Minchev et al. 2012; Martinez-Garcia 2013; Shields 2013), and does this evolution trace the growth of the black holes (and bulges)? It may be of value to explore if the amplitude/contrast of the spiral arms (Grosbøl 2013) is important for the above mentioned M_{bh} -(pitch angle) relation given the existence of a) dwarf galaxies with very faint spiral arms (e.g. Jerjen et al. 2000; Graham et al. 2003), and b) the anemic spirals in the classification scheme of van den Bergh (1976).

In Fig. 6a, the bulges of barred galaxies appear to house black holes which are, on average, a factor of two less massive than those in non-barred galaxies of the same velocity dispersion (Graham 2008a,b, Hu 2008; Graham et al. 2011). However, as was initially speculated, this result is instead due to the bar’s dynamics having elevated the velocity dispersion (Hartmann et al. 2013, see also Brown et al. 2013). That is, the barred galaxies are offset in velocity dispersion rather than black hole mass.

It is not yet established if barred galaxies follow a different distribution in the $M_{\text{bh}}-L_{\text{bulge}}$ diagram (Fig. 6b). One important, recent realisation is that because bulges of (barred and non-barred) disk galaxies follow the $M_{\text{bh}} \propto \sigma^5$ scaling relation (Fig. 6a), and the luminosity $L \propto \sigma^2$ for bulges with absolute B-band magnitudes fainter than $M_B = -20.5 \pm 1$ mag (e.g. Davies et al. 1983; Matković & Guzmán 2005; Kourkchi et

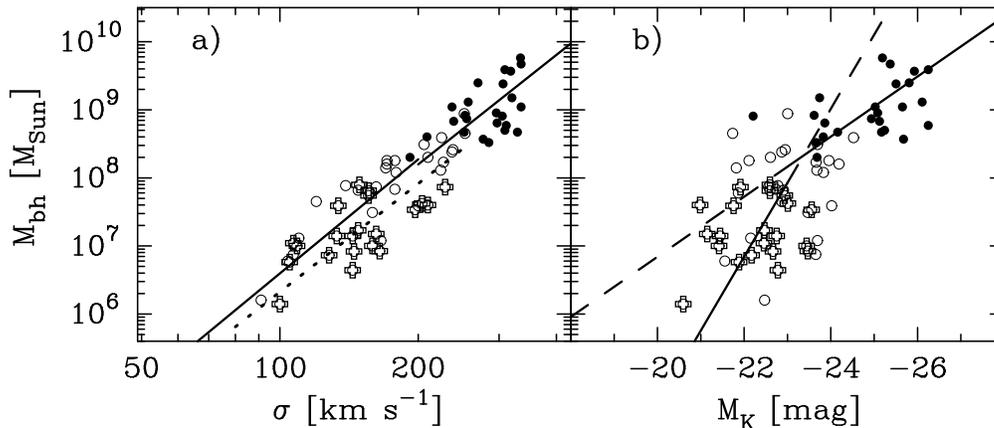


Figure 6. Black hole mass versus a) velocity dispersion and b) K -band bulge magnitude. Galaxies with depleted cores are shown by the filled circles. Galaxies without depleted cores are shown by the open symbols. Barred galaxies are shown by the crosses. Separate linear regressions have been applied to all three types in panel a), while the latter two types have been grouped together in panel b) due to the level of scatter in the current data (see Graham & Scott 2013 for more details).

al. 2012), it requires that $M_{\text{bh}} \propto L^{2.5}$ (or $M_{\text{bh}} \propto M_{\text{bulge,dyn}}^2$, if $M_{\text{dyn}}/L \propto L^{1/4}$)¹. That is, there should not be a linear $M_{\text{bh}}-M_{\text{bulge}}$ relation for these galaxies, but rather a near-quadratic relation, and this is what is observed in Fig. 6b (Graham 2012; Graham & Scott 2013; Scott et al. 2013).

5. Pseudobulges

‘Pseudobulges’ are supposed to rotate and have an exponential light profile, akin to the disk material from which they formed (Bardeen 1975; Hohl 1975; Hohl & Zhang 1979; Combes & Sanders 1981). The topic of their light profiles was already addressed in Section 2.2 with a large galaxy sample, where it was both explained why and shown that there is no physical divide at $n = 2$ in the structural diagrams, although see Fisher & Drory (2008) for an alternative view. It was also pointed out that the scaling relations involving the ‘effective’ structural parameters are curved and therefore cannot on their own be used to identify different bulge (formation) type.

5.1. Rotation

Bulges have of course been known to rotate for many years (e.g. Pease 1918; Babcock 1938; Rubin, Ford & Kumar 1973).

Merger events can create rotating elliptical galaxies (e.g. Naab, Khochfar & Burkert 2006; González-García et al. 2009; Hoffman et al. 2009), and merger simulations can also create bulges which rotate (Bekki 2010; Keselman & Nusser 2012). Classical

¹Note: Cappellari et al. (2006) report $M_{\text{dyn}}/L \propto L^{1/3}$, and the $M_{\text{dyn}}-\sigma$ relation from Cappellari et al. (2013, their figure 1) appears to show a bend at roughly $10^{11} M_{\odot}$, in the middle of the distribution where $\log[M_{\text{dyn}}/L] = 0.75$.

bulges can be spun up by a bar (Saha et al. 2012). Bar dynamics may give the illusion of rotation in classical bulges (Babusiaux et al. 2010). Williams et al. (2010) report that some boxy bulges, (previously) thought to be bars seen in projection (Combes & Sanders 1981), do not display cylindrical rotation as expected and can have stellar populations different to their disk. Qu et al. (2011) report on how the rotational delay between old and young stars in the disk of our Galaxy may be a signature of a minor merger event.

For the above reasons, rotation is not a definitive sign of bulges built via secular disk processes, and as such it can not be used to definitively identify bulge type.

5.2. Ages

From optical and near-IR colours, Peletier et al. (1999) concluded (after avoiding dusty regions) that the bulges of S0-Sb galaxies are old and cannot have formed from secular evolution more recently than $z = 3$. Bothun & Gregg (1990) had previously argued that bulges in S0 galaxies are typically 5 Gyr older than their disks. Bell & de Jong (2000) reported that bulges tend to be older and more metal rich than disks in all galaxy types, and Carollo et al. (2007) found that roughly half of their late-type spirals had old bulges. Gadotti & dos Anjos (2001) found that $\approx 60\%$ of Sbc galaxies have bulge colours which are redder than their disks. For reference, it is noted that the average Sbc spiral has a Sérsic index $n < 2$ (Graham & Worley 2008).

From spectra, Goudfrooij, Gorgas & Jablonka (1999) reported that bulges in their sample of edge-on spiral galaxies are old (like in elliptical galaxies), and have super-solar α/Fe ratios similar to those of giant elliptical galaxies. They concluded that their observations favor the ‘dissipative collapse’ model rather than the ‘secular evolution’ model. Thomas & Davies (2006) concluded, from their line strength analysis, that secular evolution is not a dominant mechanism for Sbc and earlier type spirals (see also González-Delgado et al. 2004). MacArthur, González & Courteau (2009) revealed that most bulges in all spiral galaxies have old mass-weighted ages, with $< 25\%$ by mass of the stars being young.

Given that most bulges have old mass-weighted ages, it favours a prevalence of classical bulges, many of which may co-exist with a secular-driven pseudobulge, as advocated in Erwin et al. (2003) for the S0 population, and appears to also be the case for the Milky Way (Dékány et al. 2013).

6. Compact massive bulges

Fig. 7 reveals that bulges are compact, with the smaller bulges being similar to low-mass compact elliptical galaxies in the local universe and the larger bulges being equivalent to the massive compact galaxies in the distant universe (see Dullo & Graham 2013). Gas accretion from cold streams (Bouquin 2013; Combes 2013) is expected to build disks around the high- z compact galaxies. This feeding is ultimately coplanar rather than random and thereby establishes the disk (Pichon et al. 2011; Stewart et al. 2013; Prieto et al. 2013). As suggested in Graham (2013), and see Debattista et al. (2013) and Driver et al. (2013), the high- z compact galaxies may indeed now be the old, massive bulges in today’s large disk galaxies (Dullo 2013), while the local ($z = 0$) compact elliptical galaxies may be the bulges of stripped disk galaxies, and/or some may be too small to have ever acquired a disk.

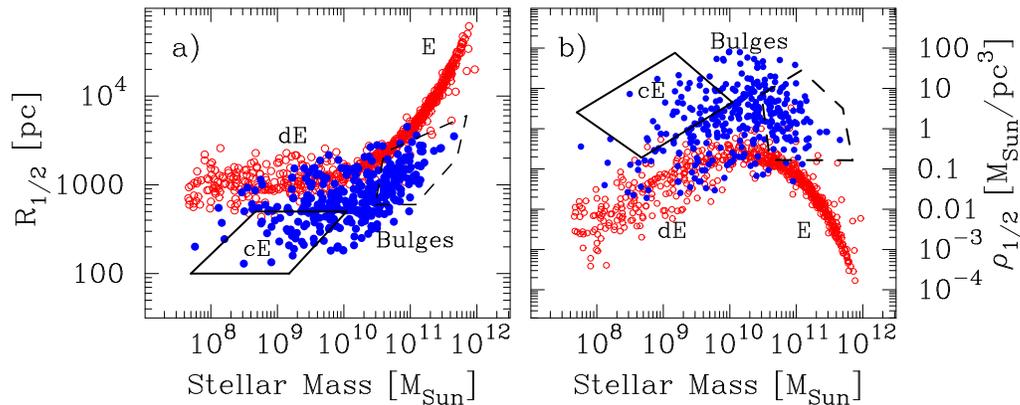


Figure 7. Size-mass and density-mass diagrams, adapted from Graham (2013). The single continuous, but curved, dwarf elliptical (dE) and elliptical (E) galaxy sequence is shown by the open circles. The denser bulges are shown by the filled circles. The dashed area shows the location of the compact, massive high- z galaxies (Damjanov et al. 2009). The solid rhomboidal shape denotes the location of compact elliptical (cE) galaxies observed in the local universe.

Acknowledgments. This research was supported under the Australian Research Councils funding scheme FT110100263.

References

- Aguerri, J.A.L., Balcells, M., Peletier, R.F. 2001, *A&A*, 367, 428
 Andredakis, Y.C., Sanders, R.H. 1994, *MNRAS*, 267, 283
 Andredakis, Y.C., Peletier, R.F., Balcells, M. 1995, *MNRAS*, 275, 874
 Babcock H.W. 1938, *PASP*, 50, 174
 Babusiaux, C., et al. 2010, *A&A*, 519, A77
 Baggett, W. E., Baggett, S. M., & Anderson, K. S. J. 1998, *AJ*, 116, 1626
 Balcells, M., Graham, A.W., Dominguez-Palmero, L., Peletier, R.F. 2003, *ApJ*, 582, L79
 Bardeen, J.M. 1975, *IAU Symp.*, 69, 297
 Begelman, M.C., Blandford, R.D., Rees, M.J. 1980, *Nature*, 287, 307
 Bekki K., 2010, *MNRAS*, 401, L58
 Bell, E.F., de Jong, R.S. 2000, *MNRAS*, 312, 497
 Berrier, J. C., Davis, B. L., Kenefick, D., et al. 2013, *ApJ*, 769, 132
 Bland-Hawthorn, J., Vlajić, M., Freeman, K.C., Draine, B.T. 2005, *ApJ*, 629, 239
 Bothun, G.D., Gregg, M.D. 1990, *ApJ*, 350, 73
 Bouquin, A. 2013, these proceedings
 Brown, J.S., Valluri, M., Shen, J., Debattista, V.P., 2013, *ApJ*, 778, 151
 Burstein, D. 1979, *ApJ*, 234, 435
 Caon, N., Capaccioli, M., D’Onofrio, M., 1993, *MNRAS*, 265, 1013
 Cappellari, M., Bacon, R., Bureau, M., et al. 2006, *MNRAS*, 366, 1126
 Cappellari, M., Emsellem, E., Krajnović, D., et al. 2011, *MNRAS*, 416, 1680
 Cappellari, M., McDermid, R. M., Alatalo, K., et al. 2013, *MNRAS*, 432, 1862
 Carollo, C.M., Scarlata, C., Stiavelli, M., Wyse, R.F.G., Mayer, L. 2007, *ApJ*, 658, 960
 Combes, F. 2013, these proceedings
 Combes, F., Sanders, R.H., 1981, *A&A*, 96, 164
 Côté, P., et al. 2006, *ApJ*, 165, 57
 Côté, P., et al. 2007, *ApJ*, 671, 1456
 Damjanov, I., et al. 2009, *ApJ*, 695, 101

- Davies, R.L., Efstathiou, G., Fall, S.M., et al. 1983, *ApJ*, 266, 41
- Davis, B. 2013, these proceedings
- Debattista, V. P., Kazantzidis, S., & van den Bosch, F. C. 2013, *ApJ*, 765, 23
- Dkny, I., Minniti, D., Catelan, M., et al. 2013, *ApJL*, in press (arXiv:1309.5933)
- de Vaucouleurs, G. 1948, *Annales d'Astrophysique*, 11, 247
- de Vaucouleurs, G. 1957, *AJ*, 62, 69
- de Vaucouleurs, G. 1958, *ApJ*, 128, 465
- de Vaucouleurs, G. 1959, in *Handbuch der Physik*, ed. S.Flügge, Springer, Berlin, p.311
- Domínguez-Tenreiro, R., Tissera, P.B., Sáiz, A. 1998, *Ap&SS*, 263, 35
- Driver, S. P., Robotham, A. S. G., Bland-Hawthorn, J., et al. 2013, *MNRAS*, 430, 2622
- Dullo, B.T. 2013, these proceedings
- Dullo, B.T., Graham, A.W. 2013, *ApJ*, 768, 36
- Erwin, P., Beltrán, J.C.V., Graham, A.W., Beckman, J.E. 2003, *ApJ*, 597, 929
- Erwin, P., Pohlen, M., & Beckman, J. E. 2008, *AJ*, 135, 20
- Faber, S.M., et al. 1997, *AJ*, 114, 1771
- Ferrarese, L., et al. 2006, *ApJS*, 164, 334
- Fisher, D.B., Drory, N. 2008, *AJ*, 136, 773
- Frankston M., Schild R. 1976, *AJ*, 81, 500
- Freeman, K.C. 1970, *ApJ*, 160, 811
- Gadotti, D.A., dos Anjos, S. 2001, *AJ*, 122, 1298
- Gavazzi, G., Donati, A., Cucciati, O., et al. 2005, *A&A*, 430, 411
- González Delgado, R. M., Cid Fernandes, R., Pérez, E., et al. 2004, *ApJ*, 605, 127
- González-García, A.C., Oñorbe, J., Domínguez-Tenreiro, R., Gómez-Flechoso, M. Á. 2009, *A&A*, 497, 35
- Goudfrooij P., Gorgas J., Jablonka P., 1999, *Ap&SS*, 269, 109
- Graham, A.W. 2008a, *ApJ*, 680, 143
- Graham, A.W. PASA, 2008b, 25, 167
- Graham, A.W. 2012, *ApJ*, 746, 113
- Graham, A.W. 2013, in "Planets, Stars and Stellar Systems", Volume 6, p.91-140, T.D.Oswalt & W.C.Keel (Eds.), Springer Publishing (arXiv:1108.0997)
- Graham, A.W., Driver, S.P. 2005, *PASA*, 22(2), 118
- Graham, A.W., Guzmán, R. 2003, *AJ*, 125, 2936
- Graham, A.W., Guzmán, R. 2004, in *Penetrating Bars through Masks of Cosmic Dust*, ed. D.L. Block et al. (Dordrecht: Kluwer Academic Publishers), 318, 723
- Graham, A. W., Jerjen, H., & Guzmán, R. 2003, *AJ*, 126, 1787
- Graham, A.W., Onken, C., Athanassoula, L., & Combes, F. 2011, *MNRAS*, 412, 2211
- Graham, A.W., Scott, N. 2013, *ApJ*, 764, 151
- Graham, A.W., Worley, C.C. 2008, *MNRAS*, 388, 1708
- Grosbøl, P. 2013, these proceedings
- Hartmann, M., Debattista, V. P., Cole, D. R., et al. 2013, *MNRAS*, submitted (arXiv:1309.2634)
- Hermann, K. 2013, these proceedings
- Hoffman, L., Cox, T.J., Dutta, S., Hernquist, L. 2009, *ApJ*, 705, 920
- Hohl, F. 1975, *IAU Symp.*, 69, 349
- Hohl, F., Zhang T.A. 1979, *AJ*, 84, 585
- Hu, J. 2008, *MNRAS*, 386, 2242
- Hubble, E. 1926, *ApJ*, 64, 321
- Hubble, E.P. 1936, *Realm of the Nebulae*, by E.P. Hubble, New Haven: Yale University Press
- Jeans, J. 1919. *Problems of Cosmogony and Stellar Dynamics*, Cambridge: Cambridge Univ. Press
- Jeans, J.H. 1928, *Astronomy & Cosmogony*, (Cambridge: Cambridge University Press), p.332
- Jerjen, H., Kalnajs, A., & Binggeli, B. 2000, *A&A*, 358, 845
- Kautsch, S.J. 2009, *PASP*, 121, 1297
- Kennefick, D. 2013, these proceedings
- Kennefick, J. 2013, these proceedings
- Kent, S. 1985, *ApJS*, 59, 115

- Keselman, J. A., & Nusser, A. 2012, MNRAS, 424, 1232
 Knapen, J.H., de Jong, R.S., Stedman, S., Bramich, D.M. 2003, MNRAS, 344, 527
 Kodaira, K., Watanabe, M., Okamura, S. 1986, ApJS, 62, 703
 Kormendy, J. 1977a, ApJ, 217, 406
 Kormendy, J. 1977b, ApJ, 218, 333
 Kormendy, J., & Bender, R. 2012, ApJS, 198, 2
 Kourkchi, E., Khosroshahi, H. G., Carter, D., et al., 2012, MNRAS, 420, 2819
 Liller, M.H. 1966, ApJ, 146, 28
 Lilly, S., Schade, D., Ellis, R., et al. 1998, ApJ, 500, 75
 MacArthur, L.A., González, J.J., Courteau, S. 2009, MNRAS, 395, 28
 Martinez-Garcia, E. 2013, these proceedings
 Matković, A., & Guzmán, R. 2005, MNRAS, 362, 289
 Minchev, I., Famaey, B., Quillen, A. C., et al. 2012, A&A, 548, A126
 Naab, T., Khochfar, S., Burkert, A. 2006, ApJ, 636, L81
 Patterson, F.S., 1940, Harvard College Observatory Bulletin, 914, 9
 Pease, F. G. 1918, Proc. of the Nat. Acad. of Sci., 4, 21
 Peletier, R.F., Balcells, M., Davies, R.L., et al. 1999, MNRAS, 310, 703
 Pichon, C., Pogosyan, D., Kimm, T., Slyz, A., Devriendt, J., Dubois, Y. 2011, MNRAS, 418, 2493
 Pierini, D., Zibetti, S., Braglia, F., et al. 2008, A&A, 483, 727
 Prieto, J., Jimenez, R., & Haiman, Z. 2013, (arXiv:1301.5567)
 Puerari, I. 2013, these proceedings
 Qu, Y., Di Matteo, P., Lehnert, M.D., van Driel, W. 2011, A&A, 530, A10
 Rubin, V.C., Ford, W.K., Krishna Kumar, C. 1973, ApJ, 181, 61
 Saha, K., Martinez-Valpuesta, I., & Gerhard, O. 2012, MNRAS, 421, 333
 Sandage, A. 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Inst. Washington)
 Sandage A., 2004, in Penetrating Bars through Masks of Cosmic Dust, ed. D.L. Block et al. (Dordrecht: Kluwer Academic Publishers), 319, 39
 Scannapieco C., White S.D.M., Springel V., Tissera P.B. 2011, MNRAS, 417, 154
 Schechtman-Rook, A. 2013, these proceedings
 Scott, N., Graham, A.W., Schombert, J. ApJ, 768, 76
 Secrest, N.J., et al. 2013, ApJ, 777, 139
 Seigar M.S., Graham A.W., Jerjen H. 2007, MNRAS, 378, 1575
 Seigar, M. S., Kennefick, D., Kennefick, J., & Lacy, C. H. S. 2008, ApJL, 678, L93
 Sérsic, J.-L. 1963, Boletín de la Asociación Argentina de Astronomía, vol.6, p.41
 Sérsic, J.L. 1968, Atlas de galaxias australes
 Shaw, M.A., Gilmore, G. 1989, MNRAS, 237, 903
 Sheth, R.K., et al. 2013, these proceedings
 Shields, D. 2013, these proceedings
 Simien, F., de Vaucouleurs, G. 1986, ApJ, 302, 564
 Simmons, B. D., Lintott, C., Schawinski, K., et al. 2013, MNRAS, 429, 2199
 Spinrad H., et al. 1978, ApJ, 225, 56
 Stewart, K. R., Brooks, A. M., Bullock, J. S., et al. 2013, ApJ, 769, 74
 Treuthardt, P., Seigar, M. S., Sierra, A. D., et al. 2012, MNRAS, 423, 3118
 Thomas D., Davies R.L., 2006, MNRAS, 366, 510
 Valencia-Enriquez, D., Puerari, I. 2013, these proceedings (arXiv:1310.4674)
 van den Bergh, S. 1976, ApJ, 206, 883
 van den Bergh, S. 1997, AJ, 113, 2054
 van der Kruit, P. C. 1979, A&AS, 38, 15
 van der Kruit, P. C. 1987, A&A, 173, 59
 van Houten C.J. 1961, Bull. Astron. Inst. Netherlands, 16, 1
 Wainscoat R.J., Freeman K.C., Hyland A.R. 1989, ApJ, 337, 163
 Williams M.J., et al. 2010, MNRAS, 414, 2163
 Wyse, R.F.G., Gilmore, G., & Franx, M. 1997, ARA&A, 35, 637
 Young, C.K., Currie, M.J. 1994, MNRAS, 268, L11