A REVIEW OF ELLIPTICAL AND DISC GALAXY STRUCTURE, AND MODERN SCALING LAWS

To appear in "Planets, Stars and Stellar Systems", Vol. 6, Springer Publishing. http://www.springer.com/astronomy/book/978-90-481-8818-5

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ABSTRACT

A century ago, in 1911 and 1913, Plummer and then Reynolds introduced their models to describe the radial distribution of stars in 'nebulae'. This article reviews the progress since then, providing both an historical perspective and a contemporary review of the stellar structure of bulges, discs and elliptical galaxies. The quantification of galaxy nuclei, such as central mass deficits and excess nuclear light, plus the structure of dark matter halos and cD galaxy envelopes, are discussed. Issues pertaining to spiral galaxies including dust, bulge-to-disc ratios, bulgeless galaxies, bars and the identification of pseudobulges are also reviewed. An array of modern scaling relations involving sizes, luminosities, surface brightnesses and stellar concentrations are presented, many of which are shown to be curved. These 'redshift zero' relations not only quantify the behavior and nature of galaxies in the Universe today, but are the modern benchmark for evolutionary studies of galaxies, whether based on observations, N-body-simulations or semi-analytical modelling. For example, it is shown that some of the recently discovered compact elliptical galaxies at $1.5 < z < 2.5$ may be the bulges of modern disc galaxies.

Subject headings: galaxy structure — galaxy scaling relations — galaxy elliptical — galaxy spiral — galaxy compact — galaxy cD, halos — galaxy nuclei — galaxy central mass deficits — galaxy excess nuclear light — galaxy bulge-disc ratios — galaxy bars — galaxy pseudobulges — galaxy bulgeless — galaxy dust — Sérsic model — core-Sérsic model — Einasto model — dark matter halos — Reynolds, Joseph B. — Hubble, Edwin —

1. Introduction

For the last century astronomers have been modelling the structure of 'nebulae', and here we focus on galaxies. A key activity performed by many astronomers, past and present, is the catergorisation of these galaxies (Sandage 2005) and the quantification of their physical properties. How big are they? How bright are they? What characteristics distinguish or unite apparent subpopulations? Answers to such questions, and the establishment of "scaling relations" between two or more galactic properties provides valuable insight into the physical mechanisms that have shaped galaxies.

Understanding how galaxies form, increasingly through the use of simulations and semi-analytic modelling (e.g. Cole 1991; White & Frenk 1991; Kauffmann et al. 1993, 2003; Avila-Reese et al. 1998; Cole et al. 2000; de Lucia et al. 2006; Bower et al. 2006; Kauffmann et al. 2004; Di Matteo et al. 2005; Croton et al. 2006; Naab et al. 2006; Nipoti et al. 2006; Covington et al. 2011; Guo et al. 2011, and references therein), requires an accurate knowledge of galaxy properties and scaling laws, as elucidated by Driver (2011). Not surpris-

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ing, our knowledge of galaxies is best in the nearby Universe — out to distances typically measured in megaparsecs rather than by redshift z — where galaxy structures can be reasonably well resolved. The properties of these galaxies provide the $z = 0$ benchmark used in the calibration of galactic evolutionary studies — both observed and simulated.

Popular scaling relations involving global galaxy parameters such as size, surface brightness, luminosity and concentration are reviewed here. As we shall see, many bivariate distributions, which are frequently assumed to be linear, are often only approximately so over a restricted luminosity range. For example, it may come as a surprise for many too learn that the useful Kormendy (1977b) relation is only the tangent to the bright arm of a continuous but curved effective radius-(surface brightness) relation which unifies dwarf and giant elliptical galaxies (section 3.2.4). Similarly, the Faber-Jackson (1976) relation with a slope of 4 represents the average slope over a restricted luminosity range to what is a curved or broken luminosity-(velocity dispersion) distribution, in which the slope is 2 rather than 4 at lower luminosities (section 3.3.3). Knowing these trends, the bulk of which cannot be established when assuming structural homology, i.e. using de Vaucouleurs' (1948) $R^{1/4}$ model, is vital if one is to measure, model and make sense of galaxies.

This article has been structured into four main sections. Section 1 provides this general overview plus a further review and introduction to galaxies on the Hubble-Jeans sequence[1]. Included are diagrams showing the location of dynamically hot stellar systems in the mass-size and mass-density plane, revealing that some high-z compact galaxies have properties equivalent to the bulges of local disc galaxies. Section 2 provides an historical account of how the radial distribution of stars in elliptical galaxies have been modelled, and the iterative steps leading to the development of the modern core-Sérsic model (section 2.2). Subsections cover the Sérsic model (section 2.1), its relation and applicability to dark matter halos (section 2.1.1), partially-depleted galaxy cores (section 2.2.1), excess nuclear light (section 2.3) and excess light at large radii in the form of halos or envelopes around giant elliptical galaxies (section 2.4). Section 3 presents and derives a number of elliptical galaxy scaling relations pertaining to the main body of the galaxy. From just two linear relations which unite the faint and bright elliptical galaxy population (section 3.1), a number of curved relations are derived (section 3.2). Several broken relations, at $M_B \approx -20.5$ mag, are additionally presented in section 3.3. For those interested in a broader or different overview of elliptical galaxies, some recent good reviews include Renzini (2006), Cecil & Rose (2007), Ciotti (2009) and Lisker (2009). Finally, the latter third of this paper is tied up in section 4 which contains a discussion of the light profiles of disc galaxies and their bulge-disc decomposition (4.1). Also included are subsections pertaining to dust (section 4.2), the difficulties with identifying pseudobulges (section 4.3), potential bulgeless galaxies (section 4.4) and methods to model bars (section 4.5). Throughout the article references to often overlooked discovery or pioneer papers are provided.

1.1. Early Beginnings

Looking out into the Milky Way arced across our night sky, the notion that we are residents within a pancake-shaped galaxy seems reasonable to embrace. Indeed, back in 1750 Thomas Wright also conjectured that we reside within a flat layer of stars which is gravitationally bound and rotating about some centre of mass. However, analogous to the rings of Saturn, he entertained the idea that the Milky Way is comprised of a large annulus of stars rotating about a distant centre, or that we are located in a large thin spherical shell rotating about some divine centre (one of the galactic poles). While he had the global geometry wrong, he was perhaps the first to speculate that faint, extended nebulae in the heavens are distant galaxies with their own (divine) centers.

As elucidated by Hoskin (1970), it was Immanuel Kant (1755), aware of the elliptically-shaped nebulae observed by Maupertuis, and working from an incomplete summary of Wright (1750) that had been published in a Hamburg

[1] This review does not encompass dwarf spheroidals, or any, galaxies fainter than $M_B \approx -14$ mag. These galaxies can not be observed (to date) at cosmologically interesting distances, and their increased scatter in the colour-magnitude relation may indicate a range of galaxy types (e.g. Penny & Conselice 2008, and references therein).

Journal[2], who effectively introduced the modern concept of disc-like galactic distributions of stars — mistakenly crediting Wright for the idea.

Using his 1.83 m "Leviathan of Parsonstown" metal reflector telescope in Ireland, Lord William Henry Parsons, the 3rd Earl of Rosse, discovered 226 New General Catalogue[3] (NGC: Dreyer 1888) and 7 Index Catalogue (IC: Dreyer 1895, 1908) objects (Parsons 1878). Important among these was his detection of spiral structure in many galaxies, such as M51 which affectionately became known as the whirlpool galaxy.

Further divisions into disc (spiral) and elliptical galaxy types followed (e.g. Wolf 1908; Knox Shaw 1915; Curtis 1918; Reynolds 1920; Hubble 1926)[4] and Shapley & Swope (1924) and Shapley (1928) successfully identified our own Galaxy's (gravitational) center towards the constellation Sagittarius (see also Seares 1928).

With the discovery that our Universe contains Doppler shifted 'nebulae' that are expanding away from us (de Sitter 1917; Slipher 1917; see also Friedmann 1922, Lundmark 1924 and the review by Kragh & Smith 2003), in accord with a redshift-distance relation (Humasson 1929, Hubble 1929)[5] — i.e. awareness that some of the "nebuale" are external objects to our galaxy — came increased efforts to catergorise and organise these different types of "galaxy". As noted by Sandage (2004, 2005), Sir James Jeans (1928) was the first to present the (tuning fork)-shaped diagram that encapsulated Hubble's (1926) early-to-late type galaxy sequence, a sequence which had been inspired in part by Jeans (1919) and later popularised by Hubble (1936a; see Block et al. 2004). Quantifying the physical properties of galaxies along this sequence, with increasing accuracy and level of detail, has occupied many astronomers since. Indeed, this review addresses aspects related to the radial concentration of stars in the elliptical and disc galaxies which effectively define the Hubble-Jeans sequence. Irregular galaxies are not discussed here.

1.2. The modern galaxy

For reasons that will become apparent, this review uses the galaxy notation of Alan Sandage and Bruno Binggeli, in which dwarf elliptical (dE) galaxies are the faint extension of ordinary and luminous elliptical (E) galaxies, and the dwarf spheroidal (dSph) galaxies — prevalent in our Local Group (Grebel 2001) — are found at magnitudes fainter than $M_B \approx -13$ to -14 mag ($\approx 10^8 M_\odot$ in stellar mass; see Figure 1a). Figure 1a reveals a second branch of elliptically-shaped object stretching from the bulges of disc galaxies and compact elliptical (cE) galaxies to ultra compact dwarf (UCD) objects (Hilker et al. 1999; Drinkwater et al. 2000; Norris & Kannappan 2011 and references therein). A *possible* connection is based upon the stripping of a disc galaxy's outer disc to form a cE galaxy (Nieto 1990; Bekki et al. 2001b; Graham 2002; Chilingarian et al. 2009) and through greater stripping of the bulge to form a UCD (Zinnecker et al. 1988; Freeman 1990; Bassino et al. 1994; Bekki 2001a). It is thought that nucleated dwarf elliptical galaxies may also experience this stripping process, giving rise to UCDs.

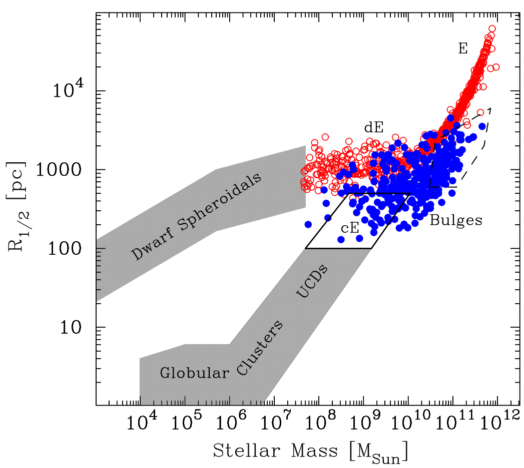
While the identification of local spiral galaxies is relatively free from debate, the situation is not so clear in regard to elliptically-shaped galaxies. The discovery of UCDs, which have sizes and fluxes intermediate between those of galaxies and (i) the nuclear star clusters found at the centres of galaxies and (ii) globular clusters (GCs: e.g. Haşegan et al. 2005; Brodie & Strader 2006), led Forbes & Kroupa (2011) to try and provide a modern definition for what is a galaxy (see also Tollerud et al. 2011). Only a few years ago there was something of a divide between GCs and UCDs — all of which had sizes less than ∼30 pc — and galaxies with sizes greater than 120 pc (Gilmore et al. 2007). However, as we have steadily increased our celestial inventory, objects of an intermediate nature have been found (e.g. Ma et al. 2007, their

[2] Freye Urtheile, Achtes Jahr (Hamburg, 1751), translated by Hastie, op. cit., Appendix B.

[3] The NGC built upon the (Herschel family's) Catalog of Nebulae and Clusters of Stars (Herschel 1864).

[4] Reynolds (1927) called Hubble's attention to pre-existing and partly-similar galaxy classification schemes which were not cited.

[5] It is of interest to note that Hubble (1934, 1936b, 1937) was actually cautious to accept that the redshifts corresponded to real velocities and thus an expanding Universe as first suggested by others. He used the term "apparent velocity" to flag his skepticism. In point of fact, Hubble & Tolman (1935) wrote that the data is "not yet sufficient to permit a decision between recessional or other causes for the redshift".



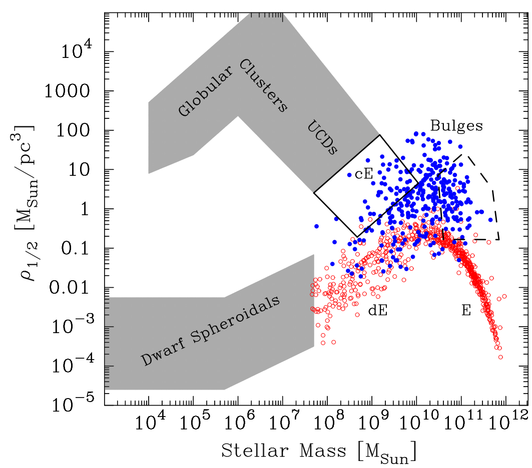


Fig. 1.— Left panel: The radius containing half of each object's light, $R_{1/2}$ (as seen in projection on the sky), is plotted against each object's stellar mass. Open circles: dwarf elliptical (dE) and ordinary elliptical (E) galaxies from Binggeli & Jerjen (1998), Caon et al. (1993), D'Onofrio et al. (1994) and Forbes et al. (2008). Filled circles: Bulges of disc galaxies from Graham & Worley (2008). Shaded regions adapted from Binggeli et al. (1984, their figure 7), Dabringhausen et al. (2008, their figure 2), Forbes et al. (2008, their figure 7), Misgeld & Hilker (2011, their figure 1). The location of the so-called "compact elliptical" (cE) galaxies is shown by the rhombus overlapping with small bulges. The location of dense, compact, $z = 1.5$ galaxies, as indicated by Damjanov et al. (2009, their figure 5), is denoted by the dashed boundary overlapping with luminous bulges. Right panel: Stellar mass density within the volume containing half each object's light, $rho_{1/2}$, versus stellar mass. The radius of this volume was taken to equal $4/3\ \times R_{1/2}$ (Ciotti 1991; Wolf et al. 2010).

Table 3), raising the question asked by Forbes & Kroupa for which, perhaps not surprisingly, no clear answer has yet emerged. While those authors explored the notion of a division by, among other properties, size and luminosity, they did not discuss how the density varies. As an addendum of sorts to Forbes & Kroupa (2011), the density of elliptically-shaped objects is presented here in Figure 1b. This is also done to allow the author to wave the following flag.

Apparent in Figure 1b, but apparently not well recognised within the community, is that the bulges of disc galaxies can be much denser than elliptical galaxies. If the common idea of galaxy growth via the accretion of a disc, perhaps from cold-mode accretion streams, around a pre-existing spheroid is correct (e.g. Navarro & Benz 1991; Steinmetz & Navarro 2002; Birnboim & Dekel 2003; see also Conselice et al. 2011 and Pichon et al. 2011), then one should expect to find dense spheroids at high-z with 10^{10}–$10^{11} M_{\odot}$ of stellar material, possibly surrounded by a faint (exponential) disc which is under development. It is noted here that the dense, compact early-type galaxies recently found at redshifts of 1.4-2.5 (Daddi et al. 2005; Trujillo et al. 2006) display substantial overlap with the location of present day bulges in Figure 1a, and that the popular dissipationless merger scenario to convert these compact high-z galaxies into today's elliptical galaxies is not without its problems (e.g. Nipoti et al. 2009). It is also noted that well-developed discs and disc galaxies are rare at the redshifts where these compact objects have been observed alongside normal-sized elliptical galaxies. Before trying to understand galaxy structure at high-redshift, and galaxy evolution — themes not detailed in this review — it is important to first appreciate galaxy structures at $z = 0$ where observations are easier and local benchmark scaling relations have been established.

2. Elliptical Galaxy Light Profiles

Over the years a number of mathematical functions have been used to represent the radial distribution of stellar light in elliptical galaxies, i.e. their light profiles. Before getting to de Vaucouleurs' $R^{1/4}$ model in the following paragraph, it seems apt to first quickly mention some early competitors. Although Plummer's (1911) internal-density model was developed for the nebulae which became know as globular clusters, because of its simplicity it is still used today by some researchers to simulate elliptical galaxies, even though, it should be noted, no modern observers use this model to describe the radial distribution of light in elliptical galaxies. Reynold's (1913) surface-density model, sometimes referred to as Hubble's (1930) model or the Reynold-Hubble model, was used to describe the nebula which became known as elliptical galaxies. It has an infinite mass and is also no longer used by observers today. The modified Hubble model (Rood et al. 1972), which also has an infinite mass, is also still sometimes used by simulators, even though, again, observers do not use this model anymore. Oemler's (1976) exponentially-truncated Hubble model, known as the Oemler-Hubble model, is also not used to represent the observed stellar distribution in elliptical galaxies because it too, like its predecessors, was simply an approximation applicable over a limited radial range, as noted by King (1978). It is interesting to note that up until the 1980s, departures at large radii from the Reynold's model were attributed to tidal-stripping by external gravitational potentials. That is, for three quarters of a century, Reynold's model — originally developed from low-quality data for one galaxy — was generally thought to describe the original, undisturbed stellar distribution in elliptical galaxies.

de Vaucouleurs' (1948, 1953) $R^{1/4}$ surface-density model had traction for many years, in part due to de Vaucouleurs (1959) arguing that it fits better than the Reynold's model used by Hubble, — a point re-iterated by Kormendy (1977a) and others — and the revelation that it fits the radially-extended data for NGC 3379 exceedingly well (de Vaucouleurs & Capaccioli 1979). Hodge (1961a,b) had however revealed that de Vaucouleurs' model was inadequate to describe faint elliptical galaxies and Hodge (1963, 1964), in addition to King (1962)[6], noted that the 3-parameter King model, with its flatter inner profile and steeper decline at large radii, did a better job. For a time, King's (1962, 1966) model became popular for describing the light distribution

[6]King (1962) also noted that his model failed to fit the inner region of bright elliptical galaxies.

in faint elliptical galaxies, at least until the exponential model — also used for the discs of spiral galaxies — was noted to provide a good description of some dwarf elliptical galaxies (Hodge 1971; Faber & Lin 1983; Binggeli et al. 1984) and that these galaxies need not have experienced any tidal truncation (a prescription of the King model with its tidal radius parameter). Lauer (1984, 1985) additionally showed that King's modified isothermal model, with its flat inner core, was inadequate to describe the deconvolved light-profiles of ordinary elliptical galaxies with "cores", i.e. galaxies whose inner light profile displays a nearly flat core. King's model does however remain extremely useful for studies of star clusters, globular clusters[7], dwarf spheroidal galaxies and galactic satellites which, unlike ordinary elliptical galaxies, can have flat cores in their inner surface brightness profile.

Today, the model of choice for describing nearby (and distant) dwarf and ordinary elliptical galaxies is Sérsic's (1963) generalisation of de Vaucouleurs' $R^{1/4}$ model to give the $R^{1/n}$ surface-density model (section 2.1). This model reproduces the exponential model when $n = 1$ and de Vaucouleurs' model when $n = 4$; it can thus describe the main body of faint and luminous elliptical galaxies. The key advantage that this model has is (i) its ability to describe the observed stellar distributions that have a range of central concentrations (known to exist since at least Reaves 1956) and (ii) it provides a very good description of the data over (almost) the entire radial extent. Indeed, departures in the light profile from a well-fit Sérsic's model invariably signal the presence of additional features or components, rather than any failing of the model. Expanding upon the Sérsic model, the core-Sérsic model (section 2.2) is nowadays used to quantify those galaxies with "cores".

Although referring to the King model, the following quote from King (1966) seems particularly insightful "... de Vaucouleurs' law appears to refer to a particular central concentration and should be appropriate only for galaxy profiles that have that concentration." While noted by others, such as Oemler (1976), Capaccioli (1985), Michard (1985) and Schombert (1986), some three decades elapsed before the relevance of King's remark to elliptical galaxies re-surfaced — albeit slowly at first — in the 1990s. Indeed, de Vaucouleurs' useful, albeit limited, $R^{1/4}$ model was referred to as a "law" for nearly half a century. However we are now more keenly aware that (even normal) elliptical galaxies possess a range of central concentrations: concentrations which are well quantified in terms of the exponent n in Sérsic's $R^{1/n}$ model (see Trujillo, Graham & Caon 2001; Graham, Trujillo & Caon 2001). Although, it should be confessed that one can still encounter papers which use $R^{1/4}$ model parameters alongside some model-independent measure of galaxy concentration, unaware of the inconsistency arising from the fact that every $R^{1/4}$ model actually has exactly the same level of concentration.

Before introducing the equation for Sérsic's model in the following section, it is pointed out that in addition to modelling what can be considered the main body of the galaxy, one can also find excess stellar light at (i) small radii in the form of nuclear (i.e. centrally located) discs and dense nuclear star clusters (section 2.3) and also at (ii) large radii in the form of halos or envelopes in cD and central cluster galaxies (section 2.4). As briefly noted above, deficits of stellar flux at the cores of massive galaxies are also observed, and a model to quantify these stellar distribution, relative to the outer non-depleted light profile, is described in section 2.2. While non-symmetrical components in elliptical galaxies can also exist, they are not addressed here given the focus on well-structured systems. Somewhat random, non-symmetrical components may be a sign of a disturbed morphology (see E.Barton's Chapter in this volume), of on-going non-uniform star formation (see S.Boissier's Chapter in this volume) or gravitationally-induced tidal features from external forces.

2.1. Sérsic's model

José Sérsic's (1963, 1968) $R^{1/n}$ model, which was introduced in Spanish, describes how the projected surface-intensity I varies with the projected radius R, such that

$$I(R) = I_e \exp\left\{-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\} \qquad (1)$$

[7]The Wilson (1975) and Elson (1987) model are also useful for describing globular clusters.

and I_e is the intensity at the 'effective' radius R_e that encloses half of the total light from the model (Ciotti 1991; Caon et al. 1993). The term b_n ($\approx 1.9992n - 0.3271$ for $0.5 < n < 10$, Capaccioli 1989) is not a parameter but is instead dependent on the third model parameter, n, that describes the shape, i.e. the concentration, of the light profile.[8] The exact value of b_n is obtained by solving the equation $\Gamma(2n) = 2\gamma(2n, b_n)$ where γ(2n,x) is the incomplete gamma function and Γ is the (complete) gamma function (Ciotti 1991). Useful Sérsic related expressions have been presented in Ciotti (1991), Simonneau & Prada (2004) and Ciotti & Bertin (1999), while Graham & Driver (2005) provide a detailed review of Sérsic's model plus associated quantities and references to pioneers of this model.

The relation between the effective surface brightness ($\mu_e = -2.5 \log I_e$) and the central surface brightness ($\mu_0 = -2.5 \log I_0$) is given by the expression

$$\mu_e = \mu_0 + 1.086b, \tag{2}$$

where we have dropped the subscript n from the term b_n for simplicity, while

$$\langle\mu\rangle_e = \mu_e - 2.5 \log[e^b n\Gamma(2n)/b^{2n}] \tag{3}$$

gives the difference between the effective surface brightness and the mean effective surface brightness ($\langle\mu\rangle_e$) within R_e. Figure 2 shows the behaviour of the Sérsic model.

Uniting CCD data with wide and deep photographic images, Caon et al. (1990, 1993, 1994) revealed that the Sérsic $R^{1/n}$ model provided a remarkably good description to the stellar distribution over a large radial range, down to surface brightnesses of $\sim$28 B-mag arcsec^{-2}, for the early-type galaxies brighter than $M_B = -18$ mag in the Virgo cluster. This work was in essence an expansion of de Vaucouleurs & Capaccioli's (1979) study of NGC 3379 which is very well-fit with $n = 4$. Different galaxies were discovered by Caon et al. (1993) to be equally well fit, but required different values of n (see also Bertin et al. 2002).

Importantly, Caon et al. (1993) additionally showed that a correlation existed between stellar concentration, i.e. the Sérsic index n, and (model-independent) galaxy size that was not due to parameter coupling in the Sérsic model (see also Trujillo et al. 2001, their section 2). One of the commonly overlooked implications of this result is that $R^{1/4}$, and similarly Petrosian (1976), magnitudes, sizes and surface brightnesses are systematically in error as a function of galaxy concentration (Graham et al. 2005; Hill et al. 2011). That is, application of a model which fails to adequately capture the range of stellar distributions will result in parameters which are systematically biased as a function of galaxy mass. For example, fitting an $R^{1/4}$ model to elliptical galaxies which are actually described by an $R^{1/n}$ model with n less than and greater than 4 will yield sizes and luminosities which are, respectively, greater than and less than the true value (e.g. Binggeli & Cameron 1991; Trujillo et al. 2001; Brown et al. 2003). Similarly, fitting an exponential model to bulges that are best described by an $R^{1/n}$ model with n less than and greater than 1 will yield sizes and luminosities which are, respectively, greater than and less than the true value (e.g. Graham 2001). Obviously one does not want to fine tune their galaxy simulations to match scaling relations that contain systematic biases due to poor measurements, and observers are therefore busy fitting $R^{1/n}$ models these days.

A good approximation to the internal-density profile associated with Sérsic's model, i.e. with its deprojection, was introduced by Prugniel & Simien (1997). Useful expressions for the dynamics, gravitational potential and forces of this model have been developed by Trujillo et al. (2002), Terzić & Graham (2005) and Terzić & Sprague (2007). Somewhat more complex than the early light-profile models, such expressions can, importantly, accommodate a range of concentrations, rather than only varying one scale radius and one scale density. Such a model is vital if one wishes to properly simulate and understand the mass spectrum of elliptical galaxies, whose Sérsic index n increases with stellar mass. While Graham & Driver's (2005) review stated that "No attempt has been made here to show the numerous scientific advances engendered via application of the $R^{1/n}$ model", this article reveals how Sérsic's model, and the core-Sérsic model 0 (subsection 2.2), have become key in unifying and understanding the galaxies around us.

[8]Ellipticity gradients result in a different Sérsic index for the major- and minor-axis, as noted by Caon et al. (1993) and later quantified by Ferrari et al. (2004).

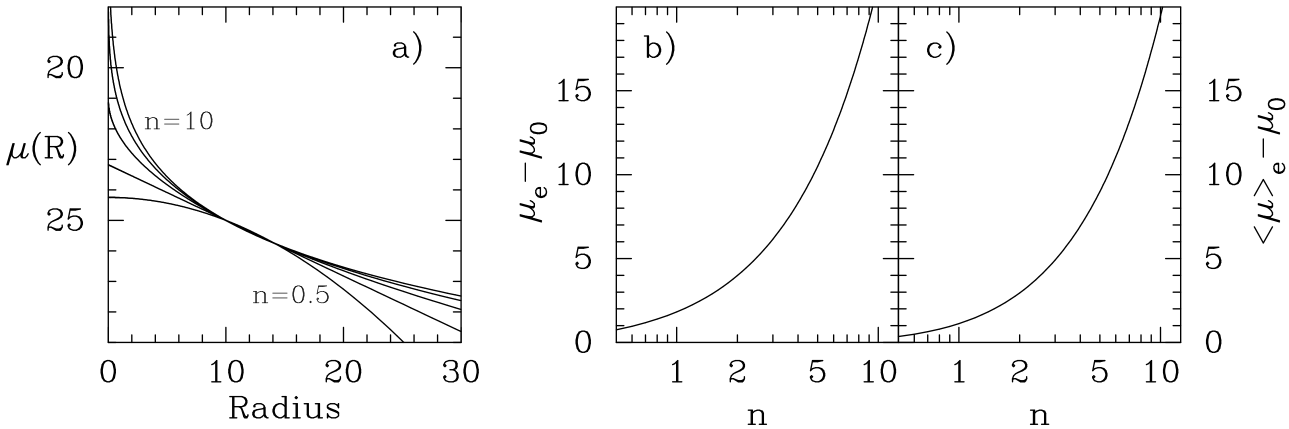


Fig. 2.— Left panel: Sérsic's $R^{1/n}$ model (equation 1) for indices $n = 0.5, 1, 2, 4$ and 10. The effective radius (R_e) and surface brightness ($\mu_e = -2.5 \log I_e$) have been arbitrarily set to 10 and 25. Right panel: Difference between the various surface brightness terms discussed in the text.

Like the majority of surface- and internal-density models from the last century, the Sérsic function is an empirical model created to match data rather than developed from theory, and as such we should be cautious before calling it a law. Attempts to find a physical explanation for de Vaucouleurs' model yielded results which helped to keep it in vogue. Dissipational models have long been touted for producing $R^{1/4}$ profiles (e.g. Larson 1969, 1974), and in the 1980s papers based on dissipationless N-body simulations of a cold clumpy collapse or the merger of disc galaxies also claimed to finally produce $R^{1/4}$ (and also Reynold) profiles (e.g. van Albada 1982; McGlynn 1984; Carlberg et al. 1986; Barnes 1988). However a closer inspection reveals clear departures from the $R^{1/4}$ profile, with the simulated profiles better described by an $R^{1/n}$ model with $n < 4$. Obviously their inability (or perhaps lack of desire, although see Farouki, Shapiro & Duncan 1983 whose non-homologous merger remnants were initially criticised by $R^{1/4}$ aficionados) to create the range of stellar concentrations now observed in elliptical galaxies highlights a limitation of these early works. Nonetheless, these pioneering studies have led to N-body simulations by Nipoti et al. (2006) and Aceves et al. (2006) — and Farouki et al. (1983), whose results with a smaller force softening appeared years ahead of their time — have now recovered a range of Sérsic profile shapes for gravitational collapses in a dark matter halo and for disc galaxy mergers, respectively.

Given the empirical nature of Sérsic's $R^{1/n}$ model, Hjorth & Madsen (1995) revealed how dissipationless merging and violent relaxation provided a physical explanation for the departure from the homologous $R^{1/4}$ model. Other works have explained how the quasi-constant specific entropy associated with the post violent-relaxation stage of elliptical galaxies results in the observed mass-dependent range of stellar concentrations in elliptical galaxies (Gerbal et al. 1997; Lima Neto 1999; Márquez et al. 2001).

It does not seem too unreasonable to speculate that elliptical galaxies, whether built by near-monolithic collapse, collisions of disc galaxies, wet or dry mergers, appear to eventually experience the same force(s) of nature that results in their radial stellar distribution depending on the total stellar mass. That is, it may not matter how the mass was accumulated into an elliptical galaxy, once it becomes a dynamically-heated, bound stellar-system, it appears to eventually obey certain universal scaling relations (see section 3).

It is interesting to note that Sérsic actually introduced his model as a way to parameterise disc galaxies which he thought were comprised of differing ratios of a disc plus an $R^{1/4}$-bulge. His model was not initially intended to fit elliptical galaxies, and as such it did not immediately threaten de Vaucouleurs' model. Credit for popularising the use of Sérsic's $R^{1/n}$ model for approximating not only lenticular[9] bulge+disc galaxies but for describing pure elliptical galaxies resides largely with Massimo Capaccioli (e.g. Capaccioli 1985, 1987, 1989; Caon et al. 1993; D'Onofrio et al. 1994)[10]. However, Davies et al. (1988) had also introduced this model for dwarf elliptical galaxies, while Sparks (1988) developed an early Gaussian seeing correction for this model, and Ciotti (1991) developed a number of associated expressions such as the velocity dispersion profile and a distribution function. The important quantification that Capaccioli and others provided is how the radial distribution of stars in elliptical galaxies, i.e. their concentration, varies with the size, luminosity and thus the mass of the elliptical galaxy (see also Cellone, Forte, & Geisler 1994; Vennik & Richter 1994; Young & Currie 1994, 1995; Graham et al. 1996; Karachentseva et al. 1996, Vennik et al. 1996). As we shall see in this article, the implications of this breakthrough have been dramatic, unifying what had previously been considered two distinct species of galaxy, namely dwarf and ordinary elliptical galaxies, previously thought to be described by an exponential and $R^{1/4}$ model, respectively.

2.1.1. Dark Matter Halos

This review would be somewhat incomplete without a few words regarding the connection between Sérsic's model and (simulated) dark matter halos. While modified theories of gravity may yet make dark matter redundant at some level, it is intriguing to note that the Prugniel-Simien (1997) internal-density model, developed to approximate the deprojected form of Sérsic's $R^{1/n}$ model, additionally provides a very good representation of the internal-density profiles of simulated dark matter halos. Merritt et al. (2006) revealed that it actually provides a better description than not only the Navarro, Frenk & White (1997) model but even a generalised NFW model with an arbitrary inner profile slope γ.

Sérsic's former student, Navarrro, independently applied Sérsic's surface-density model to the internal-density profiles of simulated dark matter halos (Navarro et al. 2004; Merritt et al. 2005). Jaan Einasto (1965) had previously developed this same function as Sérsic to describe the internal-density profiles of galaxies. Rather than a universal profile shape, as advocated by Navarro et al. (1997), a range of simulated dark matter density profile shapes is now known to vary with the dark matter halo mass (Jing & Suto 2000; Merritt et al. 2005; Del Popolo 2010 and references therein). A number of useful expressions related to this "Einasto model", which has the same functional form as Sérsic's model but is applied to the internal rather than projected density profile, can be found in Cardone et al. (2005), Mamon & Łokas (2005) and Graham et al. (2006).

An apparent "bulge-halo conspiracy" between the radial distribution of stellar mass and dark matter (after modification by baryons) has arisen in recent years, such that elliptical galaxies reportedly have *total* internal-density profiles $\rho(r)$ described by power-laws (Bertin & Stiavelli 1993; Kochanek 1995; Gavazzi et al. 2007; Buote & Humphrey 2011). These power-laws were originally claimed to be close to isothermal, such that $\rho(r) \propto r^{-2}$ (Koopmans et al. 2006, 2009; Gavazzi et al. 2007). Recent work now emphasises that only the sample average profile slope is close to -2, and that a trend in slope with galaxy size exists (Humphrey & Boute 2010; Auger et al. 2010). This is a developing field and it is worth noting that the analyses have been confined to massive galaxies with velocity dispersions greater than $\sim$175 km s^{-1}, and thus with Sérsic indices $n \gtrsim 4$ (Graham, Trujillo & Caon 2001). While the light profile shape changes dramatically as the Sérsic index n increases from $\sim$1 to $\sim$4, there is not such an obvious change in light profile shape from $\sim$4 to higher values of n (see Figure 2). The apparent isothermal profiles of elliptical galaxies, and the alleged "bulge-halo conspiracy", may turn out to be a by-product of sample selection (i.e. choosing galaxies which have approximately the same structure). It would be interesting to expand the Sloan Lens ACS (SLACS) Survey (Bolton et al. 2006) to a greater range than only bright early-type galaxies that are approximately well fit with an $R^{1/4}$ model, and to go beyond the use of simple power-laws to describe the total mass density profile once the data allows this. Two component mass models (Prugniel-Simien+Einasto) to a range of galaxy

[9] This term was introduced by Knox Shaw (1915) and Reynolds (1920) in their galaxy classification scheme.

[10] It is worth noting that D'Onofrio (2001) re-modelled the Virgo and Fornax 2-component lenticular galaxies with an $R^{1/n}$-bulge plus an exponential disc (see section 4.

masses await. Claims that "early-type galaxies are structurally close to homologous" may therefore be premature, as was the case for the distribution of stellar light in elliptical galaxies while the $R^{1/4}$ model was thought to be a law.

2.2. The core-Sérsic model

The centres of luminous galaxies have long been known to possess "cores", such that the surface-density profile flattens at the center (e.g. King & Minkowski 1966), and King & Minkowski (1972) remarked on the inability of the Reynold's and de Vaucouleurs' model to match these flattened cores in giant galaxies. Although King (1978) identified a number of galaxies thought to be well described by his model, using seeing-deconvolved ground-based images, Lauer (1983, 1984, 1985) analysed 14 galaxies with 'cores', ranging from 1.5–5.0 arcseconds in radius, revealing that they, like M87 (Young et al. 1978; Duncan & Wheeler 1980; Binney & Mamon 1982), were not exactly described by the King model which had a completely flat core. Similar conclusions, that cores existed but that they do not have flat inner surface brightness profiles, were also reported by Kormendy (1982, 1985a), creating the need for a new model to describe the stellar distribution in galaxies.

Nearly a decade later, the Hubble Space Telescope was flying and offered factors of a few improvement over the best image resolution achievable from the ground at that time. Not surprisingly, astronomers explored the centres of galaxies. In an effort to quantify these nuclear regions, after the abandonment of the King model and the lack of a flattened core in the $R^{1/4}$ model, Crane et al. (1993), Ferrarese et al. (1994), Forbes et al. (1994) and Jaffe et al. (1994) used a double power-law model to describe the inner light profiles of large galaxies. Grillmair et al. (1994), Kormendy et al. (1994) and Lauer et al. (1995) also adopted a double-power-law model but one with an additional, fifth, parameter to control the sharpness of the transition. Their model, which they dubbed the "Nuker law" for describing the nuclear regions of galaxies (after excluding any apparent excess light), has the same functional form as the double power-law model presented by Hernquist (1990, his equation 43) to describe the internal-density of galaxies (Zhao 1996).

However, as noted by the above authors, these double power-law models were never intended to describe the entire radial extent of a galaxy's stellar distribution, and they provided no connection with the outer ($R^{1/4}$-like) radial profile. This disconnection turned out to be their down fall. Due to the curved nature of the outer light profiles beyond the core, which were being fitted by the double power-law model's outer power-law, the five parameters of the Nuker model systematically changed as the fitted radial extent changed. This was first illustrated in a number of diagrams by Graham et al. (2003) who revealed that none of the Nuker model parameters were robust, and as such they could not provide meaningful physical quantities. For example, Trujillo et al. (2004) reported that the Nuker-derived core-radii were typically double, and up to a factor of five times larger, than the radius where the inner power-law core broke away from the outer $R^{1/4}$-like profile — a result reiterated by Dullo & Graham (2011, in prep.). An additional problem was that these "break radii" were being identified in the so-called "power-law" galaxies that showed no evidence of a downward departure and flattening from the inward extrapolation of the outer $R^{1/4}$-like profile. This situation arose because of the curved nature of what were actually Sérsic profiles. That is, the so-called "power-law" galaxies not only had no distinct "core" like the "core galaxies" do, but confusingly they do not even have power-law light profiles.

Given that Caon et al. (1993) and D'Onofrio et al. (1994) had established that the Sérsic function fits the brightness profiles of elliptical galaxies remarkably well over a large dynamic range (see the figures in Bertin et al. 2002), it is possible to confidently identify departures from these profiles that are diagnostic of galaxy formation. While in this and the following section we deal with partially-depleted cores — also referred to as "missing light" — in luminous galaxies (thought to be built from dissipationless mergers), the ensuing section addresses extra central light above the inward extrapolation of the outer Sérsic profile (found in galaxies that have experienced dissipation and star formation).

Building on the work of Caon et al. (1993), Graham et al. (2003) introduced the core-Sérsic model, which was applied in Trujillo et al. (2004). The model represents a modification to Sérsic's model such that it has an inner power-law core. This represented a dramatic change from what had gone before. While the Nuker team (e.g Kormendy et al. 1994; Lauer et al. 1995, 2005; Faber et al. 1997) were combining Nuker model parameters for the core with $R^{1/4}$ model parameters for the main galaxy, Graham et al. (2003), Graham & Guzmán (2003), Balcells et al. (2003), Graham (2004) and Trujillo et al. (2004) advocated the measurement of core properties, excesses and deficits of light, measured relative to the outer Sérsic model.

For the first time, the core-Sérsic model provided an expression capable of unifying the nuclear regions of galaxies with their outer regions and also providing stable physical quantities[11]. The model can be written as

$$I(R) = I' \left[1 + \left(\frac{R_b}{R}\right)^{\alpha}\right]^{\gamma/\alpha} \times \exp\left\{-b[(R^{\alpha} + R_b^{\alpha})/R_{\rm e}^{\alpha}]^{1/(\alpha n)}\right\}, \quad (4)$$

where R_b denotes the break–radius separating the inner power–law having logarithmic slope γ from the outer Sérsic function. The intensity I_b at the break–radius is such that

$$I' = I_b 2^{-(\gamma/\alpha)} \exp\left[b(2^{1/\alpha} R_b/R_{\rm e})^{1/n}\right]. \quad (5)$$

The sixth and final parameter, α, controls the sharpness of the transition between the inner (power–law) and the outer (Sérsic) regime — higher values of α indicating a sharper transition. Figure 3 shows the core-Sérsic model (with $\alpha = 100$) applied to NGC 3348.

Terzić & Graham (2005) and Terzić & Sprague (2007) provide a number of expressions related to the potential, force and dynamics.[12] The core-Sérsic model is further discussed and used by Ferrarese et al. (2006a,b), Côté et al. (2006, 2007), Kawata, Cen & Ho (2007) and Ciotti (2009).

2.2.1. *Central Mass Deficits*

The collisional construction of galaxies from the merger of lesser galaxies is thought to be a common occurrence in the Universe. Coupled with the presence of a supermassive black hole (SMBH) at the heart of most galaxies (Wolfe & Burbidge 1970; Magorrian et al. 1998), dissipationless mergers were proposed by Begelman, Blandford & Rees (1980; see also Ebisuzaki, Makino, & Okumura 1991) to explain the depleted nuclei, i.e. the cores, observed in giant elliptical galaxies (e.g. King 1978, and references therein). It is thought that core-depletion is primarily due to the gravitational slingshot (Saslaw, Valtonen, & Aarseth 1974) effect that the coalescing SMBHs — from the pre-merged galaxies — have on stars while they themselves sink to the bottom of the potential well of the newly wed galaxy.[13]

Theory predicts that the central mass deficit $M_{\rm def}$ should scale with $0.5N\, M_{\rm bh}$, where $M_{\rm bh}$ is the final (merged) black hole mass and N the number of major "dry" (i.e. gas free, dissipationless) mergers (Milosavljević & Merritt 2001; Merritt & Milosavljević 2005; Merritt 2006a,b). Graham (2004) used the core-Sérsic model to quantify the central deficit of stars relative to the inward extrapolation of the outer Sérsic profile. Figure 4 suggests that the luminous elliptical galaxies sampled have experienced an average of 1 or 2 major dry (i.e. dissipationless) mergers, a conclusion in agreement with select λCDM models of galaxy formation (Haehnelt & Kauffmann 2002; Volonteri et al. 2003).

Quantification of the central stellar deficit relative to the inward extrapolation of the outer Sérsic profile has also been applied to bright Virgo cluster galaxies by Ferrarese et al. (2006a) and Côté et al. (2007) and with the exception of VCC 798 — a lenticular (bulge plus disc) galaxy — provides similar results. Of course when an outer disc exists, a core-Sérsic bulge plus disc fit is required, otherwise the disc will bias the Sérsic parameters.[14]

[11] The core-Sérsic, and also Sérsic, model provide robust parameters beyond the core if one has sufficient data to sample the curvature in the light profile, in practice this requires radial data out to $\sim 1 R_{\rm e}$.

[12] The complex nature of this model has resulted in the appearance of alternate expressions, e.g. Spergel (2010, see his figure 3).

[13] The presence of $FUV - NUV$ colour gradients in core galaxies such as NGC 1399 suggests that they may not have been built from major, dry merger events (Carter et al. 2011). Additionally, the globular cluster specific frequency in core galaxies may be at odds with core-galaxy formation through equal-mass merger events because the fainter, intermediate luminosity elliptical galaxies may have lower specific frequencies (Harris & van den Bergh 1981). Alternative ideas for core-formation in giant galaxies have been proposed: Boylan-Kolchin et al. 2004; Nipoti et al. 2006; Martizzi et al. 2011.

[14] Trujillo et al. (2004) and Graham (2004) intentionally excluded lenticular galaxies from their publication because

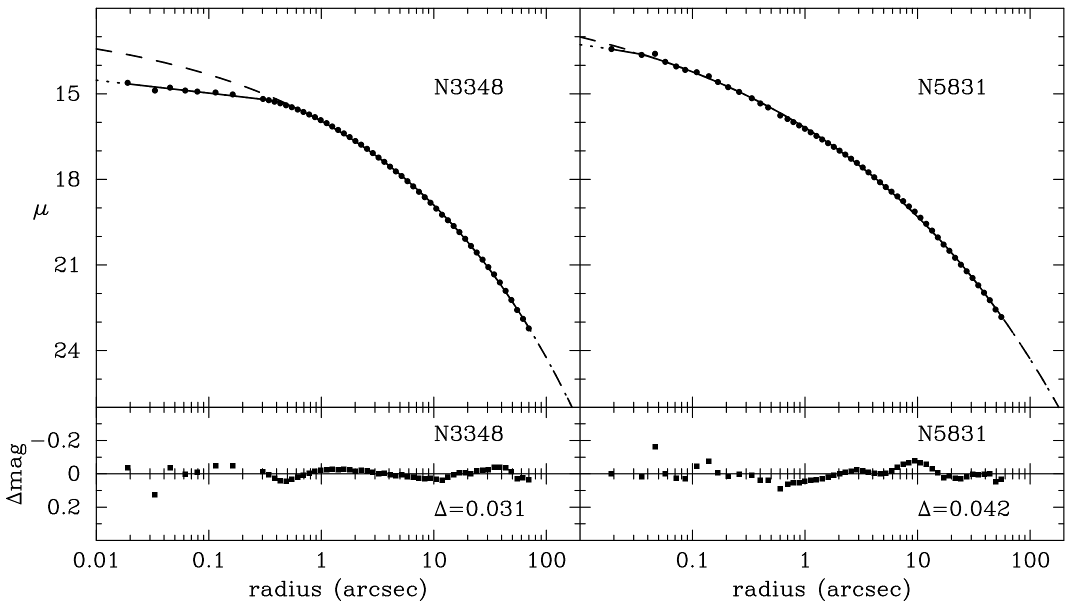


Fig. 3.— Left: Core-Sérsic model (solid line) fit to the major-axis R-band light profile of NGC 3348 (dots), with the dashed line showing the associated Sérsic component. The inner depleted zone corresponds to a stellar mass deficit of $3 \times 10^8 M_\odot$ (see Graham 2004). Right: NGC 5831 has, in contrast, no (obvious) partially depleted core and is well described by the Sérsic's model alone. The rms scatter is shown in the lower panels. Figure taken from Graham et al. (2003).

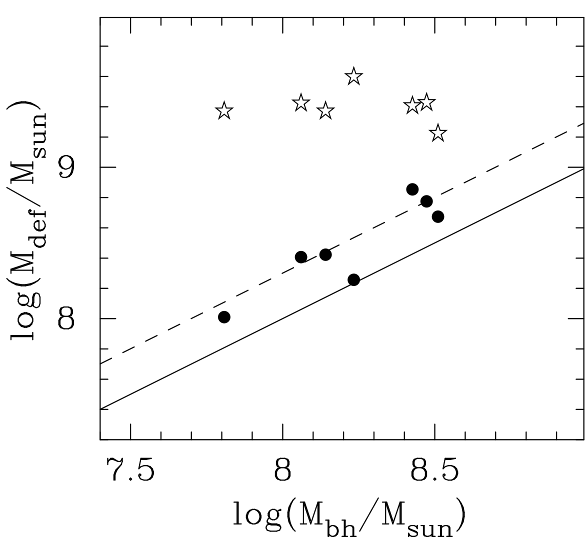


Fig. 4.— Central mass deficit for seven core galaxies derived using the core-Sérsic model (circles) and the Nuker model (stars) plotted against each galaxy's predicted central supermassive black hole mass. The solid and dashed line shows $M_{\rm def}$ equal 1 and 2 $M_{\rm bh}$, respectively. Figure adapted from Graham (2004).

2.3. Excess nuclear light

While galaxies brighter than $M_B \sim -20.5$ mag have partially depleted cores (e.g. Faber et al. 1997; Rest et al. 2001; Graham & Guzmán 2003), fainter galaxies often contain additional stellar components at their centres. Such excess nuclear light, above that of the underlying host galaxy, has long been known to exist (e.g. Smith 1935; Reaves 1956, 1977; Romanishin, Strom & Strom 1977) and was systematically studied by Binggeli et al. (1984), van den Bergh (1986) and Binggeli & Cameron (1991, 1993) in a number of dwarf elliptical galaxies. As far back as Larson (1975) it was known that simulations containing gas can account for these dense nuclear star clusters; clusters which became easier to detect with the Hubble Space Telescope (e.g. Carollo, Stiavelli & Mack 1998).

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it was felt that the community were not yet ready for an 8-parameter model (6 core-Sérsic plus 2 exponential disc parameters). Intriguingly, VCC 798 resides near the 1-to-1 line in Figure 4 when an exponential-disc plus (core-Sérsic)-bulge fit is performed (Graham, unpublished work).

For many years it was common practice to simply exclude these additional nuclear components from the analysis of the galaxy light profile (e.g. Lauer et al. 1995; Byun et al. 1996; Rest et al. 2001; Ravindranath et al. 2001). Using HST data, Graham & Guzmán (2003) simultaneously modelled the host galaxy and the additional nuclear component with the combination of a Sérsic function for the host galaxy plus a Gaussian function for the nuclear star cluster. As we will see in section 4, they also showed that the lenticular galaxies in their early-type galaxy sample could be modelled via a Sérsic-bulge plus an exponential-disc plus a Gaussian-(star cluster) decomposition of their light profile — as done by Wadadekar et al. (1999) with ground-based images. Many other studies have since modeled the nuclear star clusters seen in HST images, see Figure 5, with the combination of a nuclear component plus a Sérsic host galaxy (e.g. Grant et al. 2005; Côté et al. 2006; Ferrarese et al. 2006a; Graham & Spitler 2009).

While Graham & Guzmán (2003) and Côté et al. (2006) found that some nuclear star clusters could actually be resolved, it is not yet established what mathematical function best describes their radial distribution of stars. The closest example we have to study is of course the 30 million solar mass nuclear star cluster at the centre of the Milky Way (Launhardt et al. 2002). Graham & Spitler (2009) provided what may have been the first ever analysis after allowing for the significant contamination from bulge stars. Although they found that the cluster could be well described by a Sérsic index with $n = 3$ (see Figure 2.3, it remains to be tested how well a King model can describe the data, or at least the old stellar population known to have a core (e.g. Genzel et al. 1996). The excess nuclear light in M32 has also been well fit with an $n = 2.3$ Sérsic function (Graham & Spitler) but this too may yet be better described by a King model. What is apparent is that neither the underlying bulge nor the nuclear component are described by a power-law. Theories which form or assume such power-law cusps appear to be at odds with current observations.

2.4. Excess halo light

This section shall be somewhat cursory given R.Bower's detailed chapter on clusters and the intracluster medium in this volume.

Brightest cluster galaxies (BCGs), residing close to or at the centres of large galaxy clusters, have long been recognised as different from less luminous elliptical galaxies: their light profiles appear to have excess flux at large radii (e.g. Oemler 1976; Carter 1977; van den Bergh 1977; Lugger 1984; Schombert et al. 1986). However, before exploring this phenomenon, it is important to recall that the light profiles of large galaxies have Sérsic indices n greater than 4 (e.g. Caon et al. 1993; Graham et al. 1996).[15]. Subsequently, at large radii in big elliptical galaxies, there will be excess flux above that of an $R^{1/4}$ model fit to some limited inner radial range.

An initially puzzling result from the Sloan Digital Sky Survey (*SDSS*; York et al. 2000) survey was the lack of light profiles with Sérsic $n > 5$–6 (Blanton et al. 2005a). This was however soon resolved when Blanton et al. (2005b), Mandelbaum et al. (2005) and Lisker (2005, 2006b, 2007) pointed out a serious sky-subtraction problem with the early SDSS Photometric Pipeline (photo: Ivezić et al. 2004). The sky-value to be subtracted from each galaxy had been measured to close to the galaxy in question, and because galaxies with large Sérsic indices possess rather extended light-profiles, their outer galaxy light was actually measured and then subtracted from these galaxies. As a result, the high Sérsic index light-profiles were erroneously erased and missed from the SDSS. This resulted in the $R^{1/4}$ model appearing to provide good fits to bright elliptical galaxies, and consequently a series of papers based on structurally biased radii, magnitudes and surface brightnesses.

Bearing in mind that large elliptical galaxies have high Sérsic indices, it is important to distinguish between (i) an inadequacy of the $R^{1/4}$ model to describe what is actually a single $R^{1/n}$ profile, and (ii) a distinct physical component such as an envelope of diffuse halo light surrounding a central galaxy. Early quantitative photometry of cD galaxies (supergiant D galaxies: e.g. Matthews et al. 1964; Morgan & Lesh 1965) suggested the presence of an inner $R^{1/4}$ spheroid plus an outer exponential corona (de Vaucouleurs 1969; de Vaucouleurs & de Vaucouleurs 1970). One should

[15] As $n \to \infty$, the Sérsic model can be approximated by a power-law (see Graham & Driver 2005).

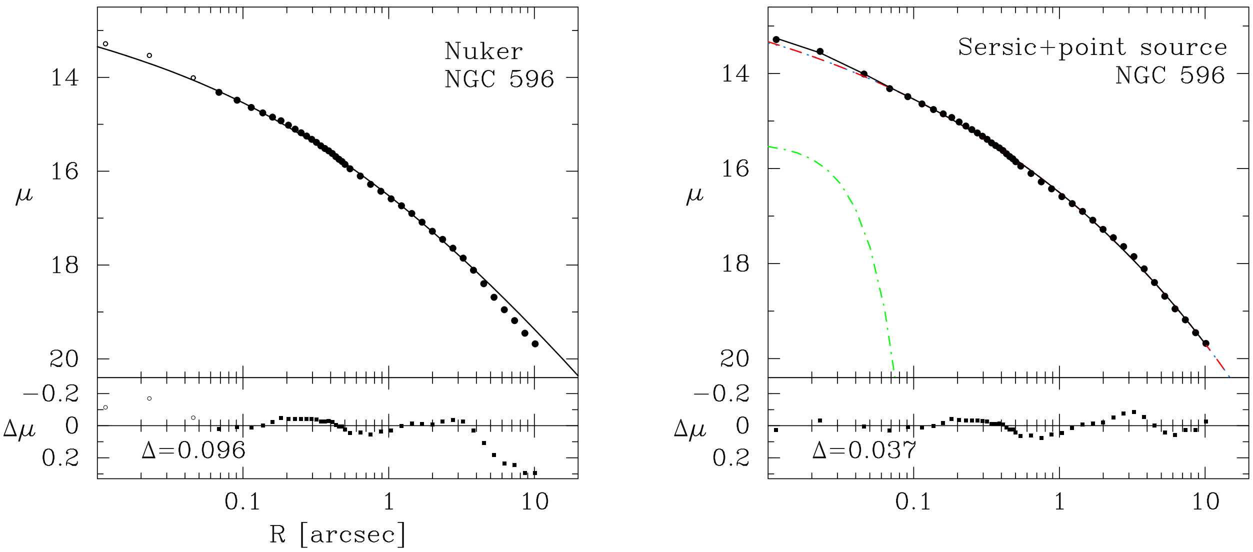

Fig. 5.— Left: 5-parameter Nuker model fit to the V-band light-profile of the nucleated galaxy NGC 596 after excluding the inner three data points (Lauer et al. 2005). Right: 3-parameter Sérsic model plus 2-parameter point-source (Gaussian) fit to the same light profile of NGC 596. With the same number of parameters, this model fits both the inner, intermediate, and outer light-profile. *Figure from Dullo & Graham (2011, in prep.).*

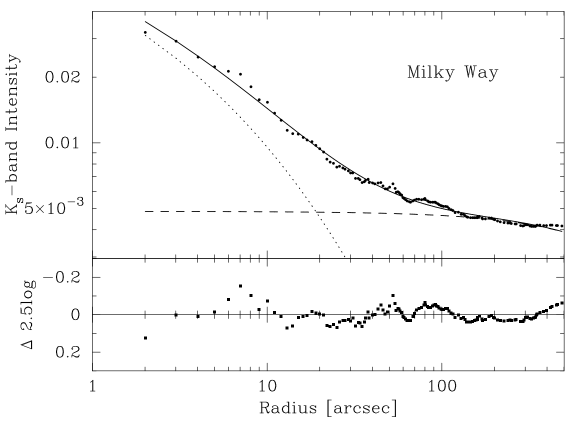

Fig. 6.— Uncalibrated, 2MASS, K_s-band intensity profile from the centre of the Milky Way, taken from Schödel et al. (2009, their Figure 2). The nuclear star cluster is modelled with a Sérsic function with $n = 3$ (dotted curve) and the underlying host bulge with an exponential function (Kent et al. 1991) that has an effective half-light radius of ∼4.5 degrees (e.g. Graham & Driver 2007) and is therefore basically a horizontal line. One parsec equals 25 arcseconds. *Figure from Graham & Spitler (2009).*

however question if this outer corona is a distinct entity or not. To answer this in the affirmative, astronomers can point to how the light profiles can display inflections marking the transition from BCG light to intracluster light. Gonzalez et al. (2005) additionally showed that the inflection in the light profiles of many BCGs was also associated with an a change in the ellipticity profile, signalling the switch from BCG light to intracluster light.

Gonzalez et al. (2005) and Zibetti et al. (2005) chose to model their BCG sample using an $R^{1/4} + R^{1/4}$ model to describe the inner galaxy plus the outer halo light. However, given that elliptical galaxies are better described by the $R^{1/n}$ model, and the desire to measure the actual concentration of halos rather than assign a fixed $R^{1/4}$ profile, Seigar et al. (2007) fitted an $R^{1/n} + R^{1/n}$ model to the light profiles of five BCGs. Not surprisingly, they found that the $R^{1/4} + R^{1/4}$ model was not the optimal representation. An $R^{1/n}$-galaxy plus an exponential-halo model was found to provide the optimal fit in three instances, with an additional galaxy having no halo detected. The associated galaxy-to-halo luminosity ratios can be found there. This re-revelation of an exponential model, rather than an $R^{1/4}$ model, describing the halo has since been confirmed by Pierini et al. (2008). Intriguing is that the halo does not trace the NFW-like dark-matter halo density profiles produced in ΛCDM simulations (section 2.1.1). Stellar halos around non-BCG galaxies have also now been reported to display an exponential radial distribution (e.g. Gadotti 2011; Tal & van Dokkum 2011).

3. Structure related scaling relations

While it is common practice, and somewhat helpful, to call elliptical galaxies fainter than about $M_B = -18$ mag by the term "dwarf elliptical" (Sandage & Binggeli 1984), it should be noted, and this section will reveal, that on all measures they appear to be the low-mass end of a continuous sequence which unifies dwarf and normal/luminous elliptical galaxies. Not only is this true in terms of their structural properties (e.g. Binggeli et al. 1984; Graham & Guzmán 2003; Gavazzi et al. 2005; Ferrarese et al. 2006a; Côté et al. 2006, 2007, 2008; Misgeld et al. 2008, 2009; Janz & Lisker 2009; Graham 2010; Chen et al. 2010; Glass et al. 2011) but even the degree of kinematically distinct components is similar (Chilingarian 2009).

There are many important relations between stellar luminosity, colour, metallicity, age, and dynamics that reveal a continuous and linear behaviour uniting dwarf and giant elliptical galaxies (e.g. Caldwell 1983; Davies et al. 1983; Binggeli et al. 1984; Bothun et al. 1986; Geha et al. 2003; Lisker & Han 2008). However, Kormendy et al. (2009, their section 8) dismiss all of these apparently unifying relations by claiming that they must not be sensitive to different physical processes which they believe have produced a dichotomy between dwarf and ordinary elliptical galaxies. They claim that it is only relations which show an apparent different behavior at the faint and bright end that are sensitive to the formation physics and the remainder are not relevant. This section explains why such non-linear relations are actually a consequence of the (dismissed) linear relations, and as such these non-linear relations actually support a continuum between dwarf and ordinary elliptical galaxies.

To begin, it should be reiterated that (dwarf and ordinary) elliptical galaxies — and the bulges of disc galaxies (section 4.1) — do not have structural homology. Instead, they have a continuous range of stellar concentrations — quantified by the Sérsic index n (Davies et al. 1988; Caon et al. 1993; D'Onofrio et al. 1994; Young & Currie 1994, 1995; Andredakis et al. 1995) — that varies linearly with both stellar mass and central surface brightness (after correcting for central deficits or excess light). A frequently unappreciated consequence of these two linear relations is that relations involving either the effective half-light radius (R_e) or the effective surface brightness (μ_e), or the mean surface brightness within R_e ($\langle\mu\rangle_e$), will be non-linear. Such curved relations have often been heralded as evidence that two different physical processes must be operating because the relation is not linear and has a different slope at either end. To further complicate matters, sample selection which includes faint and bright elliptical galaxies, but excludes the intermediate-luminosity population, can effectively break such continuously curved relations into two apparently disconnected relations, as can selective colour-coding.

There are three distinct types of (two-parameter) relations involving the properties of elliptical galaxies: (i) linear relations which are taken to reveal the unified nature of dEs and Es; (ii) curved relations revealing a continuity that had in the past been mis-interpreted to indicate that distinct formation process must be operating; and (iii) broken relations which imply that two physical mechanisms are operating. In the following sections we shall learn how the linear relations result in the existence of curved relations when using effective radii and surface brightnesses. We shall also see that the transition in the broken relations occurs at $M_B \approx -20.5$ mag and thus has nothing to do with the previously held belief that dEs and Es are two distinct species separated at $M_B = -18$ mag (Wirth & Gallager 1984; Kormendy 1985b, 2009).

3.1. Linear relations

This section introduces two key relations, from which a third can be derived, involving structural parameters. They are the luminosity-concentration (L–n) relation and the luminosity-

(central density)[16] (L–μ_0) relation. We shall use the Sérsic shape parameter n to quantify the central concentration of the radial light profile, and use the projected central surface brightness μ_0 as a measure of the central density.[17]

It is noted that one can expect a certain level of scatter in the L–n and L–μ_0 diagrams because both the central density and the radial concentration of stars that one observes depends upon the chance orientation of one's triaxial galaxy (Binney 1978). This is of course also true for measurements of effective surface brightness, half-light radii, velocity dispersions, etc. To have the best relations, it is important that we use Sérsic parameters from elliptical galaxies rather than parameters from single-Sérsic fits to samples of elliptical and lenticular galaxies given the two-component (2D-disc plus 3D-bulge) nature of the lenticular galaxies. Given the offset nature of bulges and elliptical galaxies in the L–n diagram (e.g. Graham 2001; see also Möllenhoff & Heidt 2001) it is also important that bulges not be combined in this section's analysis of elliptical galaxy scaling relations.

3.1.1. Luminosity-(central surface brightness) relation

Caldwell (1983; his Figure 6) and Bothun et al. (1986, their figure 7) revealed that, fainter than $M_B \approx -20.5$ mag, there is a continuous linear relation between luminosity and central surface brightness. Furthermore, Binggeli et al. (1984, their figure 11) and Binggeli & Cameron (1991, their figure 9 and 18) revealed that, when using the inward extrapolation of King models, the L–μ_0 relation is continuous and roughly linear from $-12 > M_B > -23$ mag. This same general result was also highlighted by Jerjen & Binggeli (1997) and Graham & Guzmán (2003) when using the inward extrapolation of the Sérsic model. The benefit of this approach is that one's central surface brightness is not biased by the presence of a depleted core or any additional nuclear components within the host galaxy. Figure 7a displays the elliptical galaxy (M_B, μ_0) data set from Graham & Guzmán (2003) fit by the expression

$$M_B = 0.67\mu_{0,B} - 29.5. \qquad (6)$$

The actual central surface brightness of the luminous "core galaxies" is shown in Figure 7a, rather than the value obtained from the inward extrapolation of their outer Sérsic profile. As such these "core galaxies" were excluded from the fit, but see the discussion in section 3.3. As an aside, if the central supermassive black hole mass $M_{\rm bh}$ in elliptical galaxies is directly related to the central stellar density (see Graham & Driver 2007), then the connections between $M_{\rm bh}$ and the global galaxy properties, such as total mass and velocity dispersion, may be secondary.

3.1.2. Luminosity-concentration relation

The linear relation between luminosity and Sérsic index, or strictly speaking the logarithm of these quantities, has been shown many times (e.g. Young & Currie 1994; Jerjen & Binggeli 1997; Graham & Guzmán 2003; Ferrarese et al. 2006a). This continuous relation between magnitude and concentration[18] for elliptical galaxies had of course been recognised before (e.g. Ichikawa et al. 1986, their figure 11). The following M_B–n expression is shown in Figure 7c, again matched to the sample of elliptical galaxies compiled by Graham & Guzmán (2003).

$$M_B = -9.4\log(n) - 14.3. \qquad (7)$$

Graham & Guzmán (2003) excluded two-component lenticular galaxies fit by others with a single-component Sérsic model. It may be prudent to continue to exclude these galaxies even after a Sérsic-bulge plus exponential disc fit because the M_B–n relation defined by bulges, at least in spiral galaxies, is different to that defined by elliptical galaxies (Graham 2001, his figure 14).

3.1.3. Concentration-(central surface brightness) relation

Combining the above two equations provides an expression between central surface brightness and

[16] Here the "central density" refers to the density prior to core depletion in giant elliptical galaxies or the growth of additional nuclear components in smaller elliptical galaxies.

[17] To convert from the surface density to the internal density, one can use equation 4 from Terzić & Graham (2005).

[18] Graham et al. (2001) contains a review of various concentration indices used over the decades, while Trujillo et al. (2001) was the first to quantify the monotonic relation between Sérsic index and concentration.

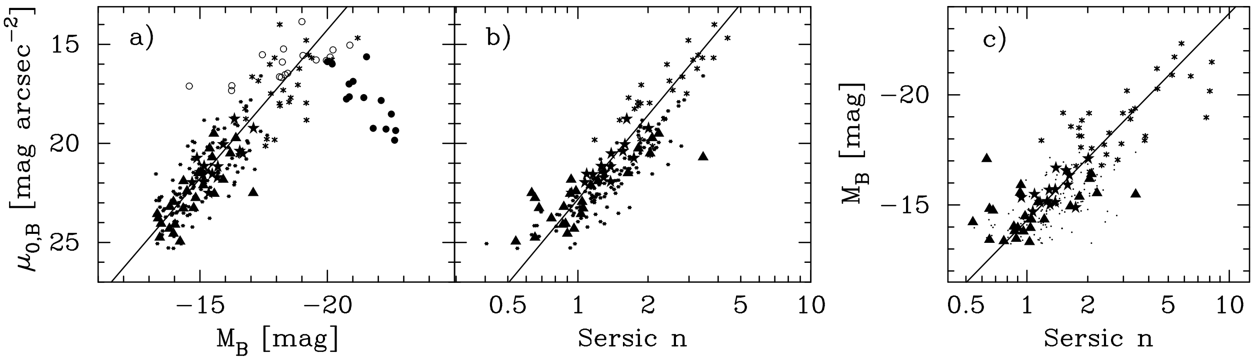

Fig. 7.— Linear relations between the observed B-band central surface brightness ($\mu_{0,B}$) with a) the absolute B-band magnitude M_B and b) the Sérsic index n for a sample of elliptical galaxies. Panel c) shows the galaxy magnitudes versus the Sérsic indices, with the line given by equation 7. The "core galaxies" (large filled circles) with partially depleted cores can be seen to have lower central surface brightnesses than the relation in panel a). Inward extrapolation of their outer Sérsic profile yields μ_0 values which follow the linear relation, as previously noted by Jerjen & Binggeli (1997). The data have come from the compilation by Graham & Guzmán (2003, their figure 9). Dots represent dE galaxies from Binggeli & Jerjen (1998), triangles represent dE galaxies from Stiavelli et al. (2001), large stars represent Graham & Guzmán's (2003) Coma dE galaxies, asterix represent intermediate to bright E galaxies from Caon et al. (1993) and D'Onofrio et al. (1994), open circles represent the so-called "power-law" E galaxies from Faber et al. (1997) and the filled circles represent the "core" E galaxies from these same Authors.

Sérsic index such that

$$\mu_0 = 22.8 - 14.1 \log(n), \tag{8}$$

which is shown in Figure 7b, where it can be seen to be roughly applicable for values of $n \gtrsim 1$.

3.2. Curved relations

This section explains why, as a direct result of the above linear relations — which unite dwarf and giant elliptical galaxies — expressions involving either the effective half-light radius R_e, the associated effective surface brightness μ_e at this radius, or the mean surface brightness $\langle\mu\rangle_e$ enclosed within this radius, are curved.

3.2.1. Luminosity-(effective surface brightness) relation

The following analysis is from Graham & Guzmán (2003).

Given the empirical M_B–n relation (equation 7), one knows what the expected value of n is for some value of M_B. One can then convert the empirical M_B–μ_0 relation (equation 6) into an M_B–μ_e relation using the exact relation between μ_0 and μ_e which depends only on the value of n (equation 2). Doing so, one obtains the expression

$$\begin{aligned}\mu_e &= 1.5M_B + 44.25 + 1.086b, \\ &= 1.5[M_B + 14.3] + 22.8 + 1.086b, \end{aligned} \tag{9}$$

where $b \approx 1.9992n - 0.3271$ and equation 7 is used to replace n in terms of M_B, such that $n = 10^{-(14.3+M_B)/9.4}$.

One can similarly convert the empirical M_B–μ_0 relation (equation 6) into an M_B–$\langle\mu\rangle_e$ relation using the exact relation between μ_0 and $\langle\mu\rangle_e$ which also depends only on the value of n (equation 3). Doing this, one obtains the expression

$$\langle\mu\rangle_e = 1.5M_B + 44.25 + 1.086b - 2.5 \log\left[\frac{e^b n\Gamma(2n)}{b^{2n}}\right], \tag{10}$$

where again $b \approx 1.9992n - 0.3271$ and equation 7 is used to replace n in terms of M_B. These curves can be seen in Figure 8 (adapted from Graham & Guzmán 2004).

Binggeli et al. (1984, their figure 8) and Capaccioli & Caon (1991) previously showed with em-

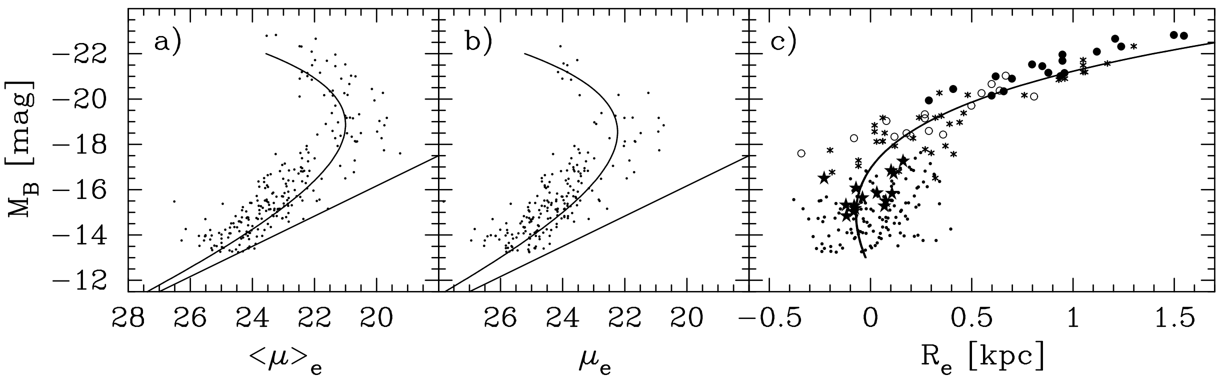

Fig. 8.— Elliptical galaxy B-band magnitude versus a) mean effective surface brightness (equation 10), b) effective surface brightness (equation 9), and c) effective radius (equation 11). The continuous, curved relations are predictions from the observed linear relations in Figure 7. The slight mismatch seen here arises from the rough fitting-by-eye of the linear relations. The data points have come from the compilation by Graham & Guzmán (2003, their figure 9).

pirical data that the M_B–$\langle\mu\rangle_{\rm e}$ relation is curved. What was new in Graham & Guzmán (2003) was the explanation. In the past, evidence of non-linear relations involving parameters from dwarf and giant elliptical galaxies were heralded as evidence of a dichotomy. Coupled with galaxy sample selection that excluded the intermediate population, and therefore resulted in two apparently disconnected relations, acted to further convince some that they were dealing with two classes of object.[19]

3.2.2. *Size-Luminosity relation*

Now that we know how to play this game, one can additionally make predictions for relations involving the effective radius $R_{\rm e}$ because we know that the luminosity $L = 2\pi\langle I\rangle_{\rm e}R_{\rm e}^2$, with $\langle\mu\rangle_{\rm e} = -2.5\log\langle I\rangle_{\rm e}$. As explained in Graham & Worley (2008, their section 5.3.1), one can derive the size-luminosity relation such that

$$\log R_e[\mathrm{kpc}] = \frac{M_B}{10} + 1.066 + 0.434n + 0.5\log\left[\frac{b^{2n}}{\mathrm{e}^b n\Gamma(2n)}\right] \quad (11)$$

[19]A simple one-dimensional example of sample bias would be a survey of the average physical properties, such as size or mass, of people at a primary school. One would measure the properties of children and adults, but miss the bridging population which reveals a continuity and thus unification of the species.

for $0.5 < n < 10$, with $b \approx 1.9992n - 0.3271$ and where equation 7 is used to replace n in terms of M_B. This size-luminosity relation for elliptical galaxies is shown in Figure 8c along with real galaxy data.

Binggeli et al. (1984, their figure 7; cf. Misgeld & Hilker 2011, their figure 7) also demonstrated, with empirical data, that the $L - R_e$ relation for dwarf and giant elliptical galaxies is curved. Their diagram, in addition to Figure 8c seen here, reveals why studies which only sample bright elliptical galaxies are often contempt to simply fit a straight line (e.g. Kormendy 1977b). The explanation for why this happens is of course akin to approximating the Earth as flat when one (forgivably) does not sample enough of what is actually a curved profile. As Graham et al. (2006, their figure 1b) re-revealed recently, and as reiterated by Bernardi et al. (2007), a sample of massive elliptical galaxies will have a steeper size-luminosity relation than a sample of ordinary elliptical galaxies, which will in turn have a steeper size-luminosity relation than a sample of dwarf elliptical galaxies because the size-luminosity relation is curved. Graham & Worley (2008) explains why the $L - R_e$ relation given by equation 11, based on two linear relations and the functional form of Sérsic's model, is curved.

Interestingly, due to the linear relations between magnitude, central surface brightness and the logarithm of the Sérsic exponent n, the use of faint isophotal radii results in what is roughly a linear size-luminosity relation (e.g. Oemler 1976; Strom & Strom 1978; Forbes et al. 2008, their figure 3; van den Bergh 2008), with the bright-end slope dependent on the adopted isophotal limit or Petrosian radius used. The implications of this important observation shall be detailed elsewhere.

Helping to propagate the belief that dwarf and ordinary elliptical galaxies are distinct species, Dabringhausen et al. (2008) and Lisker (2009) fit a double power-law to their curved size-luminosity relation for dwarf and ordinary elliptical galaxies, thus yielding distinct slopes at the faint and bright end. In addition, the interesting study by Janz & Lisker (2008) reported small deviations from the predicted curved relation. However, galaxies that are well described by Sérsic's function and which follow linear M–n and M–μ_0 relations *must* follow a single curved M–$R_{\rm e}$ relation. The deviations that they found are therefore mirroring a) the inadequacy of the fitted linear relations to the M–n and M–μ_0 distribution (a point noted in the caption of Figure 8) and/or b) poor fitting Sérsic models to their sample of elliptical *and* disc galaxies. Adding uncertainties to the linear relations in section 3.1, and propagating those through to the predicted M–$R_{\rm e}$ relation is required before we can claim evidence of significant deviations. However, searching for such second order effects may indeed be interesting given the different types of dwarf galaxies that are emerging (Lisker et al. 2007).

3.2.3. Size-concentration relation

One can additionally derive an expression relating $R_{\rm e}$ and n by substituting the magnitude from the empirical M_B–n relation, expressed in terms of n (equation 7), into the size-luminosity relation (equation 11) to give

$$\log R_e[{\rm kpc}] = 0.434n - 0.364 - 0.94\log(n) + 0.5\log\left[\frac{b^{2n}}{{\rm e}^b n\Gamma(2n)}\right]. \quad (12)$$

While the M_B–n relation is linear, the $R_{\rm e}$–n relation is curved, as can be seen in Figure 9.

In passing it is noted that the form of this relation (equation 12) matches the bulge data from Fisher & Drory (2010, their Figure 13). They interpret the departure of the low-n bulges ($n < 2$) from the approximately linear relation defined by the high-n bulges ($n > 2$) to indicate that a different formation process is operating to produce the less concentrated "pseudobulges". However, based upon linear unifying relations that span the artificial $n = 2$ divide, we know that this $R_{\rm e}$–n relation must be curved. Without an understanding of this relation, and other curved relations (e.g. Greene, Ho & Barth 2008), they have at times been misinterpretted and used to claim the existence of different physical processes (see section 4.3 for a discussion of pseudobulges: Hohl 1975 and references therein).

It may be worth better defining the behavior of the $R_{\rm e}$–n relation at small sizes in Figure 9. The data from Davies et al. (1988) suggests than when $n = 0.5$, values of $R_{\rm e}$ may range from 1 kpc down to 0.2 kpc (Caon et al. 1993, their figure 5). Such a reduction to the flattening of the $R_{\rm e}$–n distribution, below $n \approx 1$, may in part arise from the inclusion of dwarf spheroidal galaxies (see Misgeld & Hilker 2011, their figure 1).

3.2.4. Size-(effective surface brightness) relation

As discussed in Graham (2010), the first two linear relations in Figure 7 naturally explain the curved $\langle\mu\rangle_{\rm e}$–$R_{\rm e}$ relation in Figure 10. From the empirical μ_0–n relation (equation 8, Figure 7b), one can convert μ_0 into $\langle\mu\rangle_{\rm e}$ using equations 2 and 3. The effective radius $R_{\rm e}$ is acquired by matching the empirical M_B–μ_0 relation (equation 6, Figure 7a) with the absolute magnitude formula

$$M = \langle\mu\rangle_{\rm e} - 2.5\log(2\pi R^2_{\rm e,kpc}) - 36.57, \quad (13)$$

(see Graham & Driver 2005, their equation 12). Eliminating the absolute magnitude gives the expression

$$\log R_{\rm e} = \frac{1}{5}\left\{\frac{\langle\mu\rangle_{\rm e}}{3} - 9.07 + 0.72b - 1.67\log\left(\frac{n{\rm e}^b\Gamma(2n)}{b^{2n}}\right)\right\}, \quad (14)$$

in which we already know the value of n associated with each value of $\langle\mu\rangle_{\rm e}$. This is achieved by (again) using the empirical μ_0–n relation (equation 8) with equations 2 and 3, such that

$$\langle\mu\rangle_{\rm e} = 22.8 + 1.086b - 14.1\log(n) - 2.5\log\left[\frac{n{\rm e}^b\Gamma(2n)}{b^{2n}}\right] \quad (15)$$

and $b \approx 1.9992n - 0.3271$. Equation 14, obtained from two linear relations involving Sérsic parameters, is a curved relation that is shown in Figure 10. Overplotted this predicted relation are data points from real galaxies.

For those who may have the Sérsic parameter set (R_e, μ_e, n), one can use equation 3 to convert μ_e into $\langle\mu\rangle_e$ if one wishes to compare with the relation given by equation 14. For those who may have the parameter set (R_e, μ_e), perhaps obtained with no recourse to the Sérsic model, equation 14 can easily be adjusted using equation 3 to give a relation between R_e and μ_e such that

$$\log R_e = \frac{\mu_e}{15} - 1.81 - 0.5 \log\left(\frac{n e^b \Gamma(2n)}{10^{0.29b}\, b^{2n}}\right), \quad (16)$$

where the value of n associated with the value of μ_e is given by

$$\mu_e = 22.8 + 1.086b - 14.1 \log(n). \quad (17)$$

To summarise, due to the linear relations in Figure 7 which connect dwarf and ordinary elliptical galaxies across the alleged divide at $M_B = -18$ mag (Kormendy 1985), or at $n = 2$ (Kormendy & Kennicutt 2004), coupled with the smoothly varying change in light profile shape as a function of absolute magnitude, the $\langle\mu\rangle_e$-R_e and μ_e-R_e relations are expected to be curved (Figure 10), as previously shown with empirical data by, for example, Capaccioli & Caon (1991). This also explains why the fitting of a linear relation to (R_e, μ_e) data by Hoessel et al. (1987) resulted in slopes that depended on their galaxy sample magnitude.

The Kormendy relation is a tangent to the bright arm of what is actually a curved distribution defined by the relation given by equation 14 that is taken from Graham (2010). The apparent deviant nature of the dwarf elliptical galaxies from the approximately linear section of the bright-end of the $\langle\mu\rangle_e$-R_e distribution does not necessitate that a different physical process be operating. Moreover, as noted by Graham & Guzmán (2004) and Graham (2005), galaxies which appear to branch off at the faint end of the Fundamental Plane (Djorgovski & Davis 1987) — the flat portion at the bright end of a curved hypersurface — also need not have formed from different physical mechanisms. Simulations that assume or reproduce a linear $\langle\mu\rangle_e$-R_e or μ_e-R_e relation, across

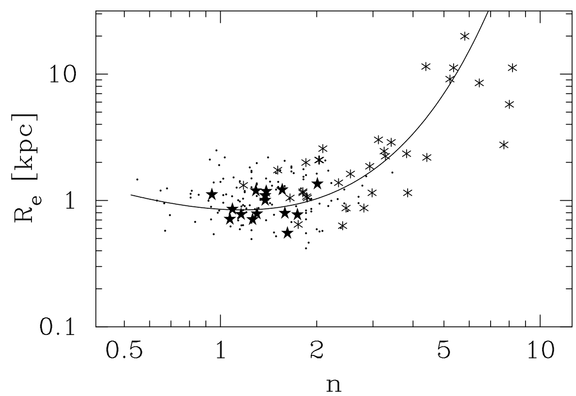

Fig. 9.— Equation 12 is over-plotted empirical data. Symbols have the same meaning as in Figure 7.

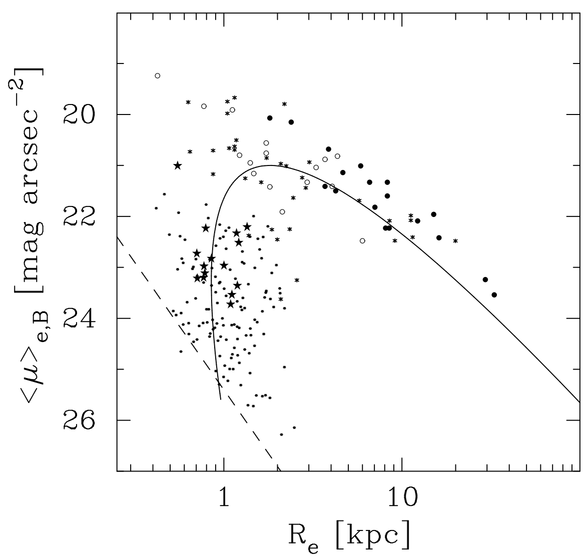

Fig. 10.— Due to the observed linear relations in Figure 7, the relation between the effective radius (R_e) and the mean surface brightness within this radius ($\langle\mu\rangle_e$) is highly curved for elliptical galaxies. The dashed line shows the $M_B = -13$ mag limit for the Virgo cluster.

too great a magnitude range, have failed to mimic the continuous curved distribution defined by real elliptical galaxies. The same remark is true for simulations of the 'Fundamental Plane'.

3.3. Broken relations

3.3.1. Luminosity-(central surface brightness) relation

While the relation between a galaxy's absolute magnitude and *extrapolated* central surface brightness is remarkably linear (section 3.1.1), there is a clear break in this relation when using the *actual* central surface brightness at the luminous end of the distribution (Figure 7a). This departure from the M_B-μ_0 relation by elliptical galaxies brighter than $M_B \approx -20.5$ mag ($M > 0.5$-$1 \times 10^{11} M_\odot$) was addressed by Graham & Guzmán (2003) in terms of partially depleted cores relative to the outer Sérsic profile (see also Graham 2004; Trujillo et al. 2004; Merritt & Milosavljević 2005; Ferrarese et al. 2006a; Côté et al. 2007). This transition has nothing to do with the alleged divide between dwarf and giant elliptical galaxies at around $M_B = -18$ mag, but is instead directly related with the Sérsic versus core-Sérsic transition at around $M_B = -20.5$ mag.

As noted in section 2.2.1, such partially depleted cores in luminous core-Sérsic galaxies are thought to have formed from dry, dissipationless galaxy merger events involving the central coalescence of supermassive black holes (Begelman, Blandford, & Rees 1980; Ebisuzaki, Makino, & Okumura 1991; but see footnote 13) and resulted in Trujillo et al. (2004) advocating a "new elliptical galaxy paradigm" based on the presence of a central stellar deficit versus either none or an excess of light, an approach embraced by Ferrarese et al. (2006a), Côté et al. (2007) and others.

Further evidence for a division at $M_B = -20.5$ mag comes from the tendency for the brighter galaxies to be anisotropic, pressure supported elliptical galaxies having boxy isophotes, while the less luminous early-type galaxies may have discy isophotes and often contain a rotating disc (e.g. Carter 1978, 1987; Davies et al. 1983; Bender et al. 1988; Peletier et al. 1990; Jaffe et al. 1994). Core galaxies also tend to be more radio loud and have a greater soft X-ray flux (e.g. Ellis & O'Sullivan 2006; Pellegrini 2010; Richings, Uttley & Körding 2011, and references therein).

It was, in part, from a diagram of central surface brightness versus magnitude that led Kormendy (1985b, his figure 3) to advocate a separation of dwarf and normal elliptical galaxies at $M_B = -18$ mag. However, as noted by Graham & Guzmán (2003), his sample was missing the bridging population near $M_B = -18 \pm 1$ mag. Excluding galaxies of this magnitude from Figure 7a would also result in two apparently disjoint relations nearly at right angles to each other. It is therefore easy to understand how one may quickly reach the wrong conclusion from an incomplete diagram. Although, Strom & Strom (1978, their figure 8; see also Binggeli et al. 1984) had already revealed that a linear relation exists between magnitude and central surface brightness from $-18.4 < M_V < -21.6$ mag, spanning the magnitude gap in Kormendy (1985b). Nonetheless, Faber & Lin (1983) had just observed that three of their six dwarf elliptical galaxies had near-exponential light profiles, leading them to speculate that dEs are more closely related to "exponential systems" than (tidally truncated) elliptical galaxies, and Wirth & Gallagher (1984, see also Michard 1979) had also just advocated a division between exponential-dwarf and $R^{1/4}$-giant elliptical galaxies.

To further confound matters, Kormendy (1985b) had the slope wrong for the distribution of dwarf elliptical galaxies in his M–μ_0 diagram, which had two consequences. First, the bright end of his dwarf elliptical galaxy distribution did not point towards the faint-end of his luminous elliptical galaxy distribution, and thus there was no suggestion of a connection. This misrepresentation is unfortunately still propagated today (e.g. Tolstoy et al. 2009, their figure 1), although Kormendy et al. (2009) have now corrected this. Second, two points representing flattened disc galaxies were added at the bright end of the mis-aligned dwarf elliptical galaxy sequence by Kormendy (1985b), implying a connection between dwarf elliptical galaxies and disc galaxies rather than ordinary elliptical galaxies.

A decade later, the Astronomy and Astrophysics Review paper by Ferguson & Binggeli (1994; their Figure 3) had a big question mark as to "how" and indeed "if" dwarf and ordinary elliptical galaxies might connect in this diagram.

When galaxies spanning the gap in Kormendy's (1985b) analysis were included by Faber et al. (1997, their figure 4c), and shown to follow a trend consistent with the relation from Strom & Strom (1978) and Binggeli et al. (1984), in which the central surface brightness became fainter with decreasing galaxy luminosity Faber et al. (1997) suggested that this behavior in their data was spurious and due to limited resolution — such was the belief in a discontinuity separating dwarf and ordinary elliptical galaxies. At the same time, Jerjen & Binggeli (1997) argued exactly the opposite, suggesting that it was instead the "core" galaxies which had been displaced in the M–μ_0 diagram from a linear M–μ_0 relation. rather than wrong central surface brightness measurements for the faint (non-dwarf) elliptical galaxies. As Graham & Guzmán (2003) and Graham (2004) later explained, in terms of a ∼0.1 percent central mass deficit relative to the outer Sérsic profile in galaxies brighter than $M_B \approx -20.5$ mag, Jerjen & Binggeli (1997) were right, supporting the views expressed by Binggeli et al. (1984) on a continuity between dwarf elliptical and ordinary elliptical galaxies across the alleged divide at $M_B \approx -18$ mag.

An alternate view

Before continuing, two points regarding the $M-\mu_0$ diagram in Kormendy et al. (2009, their figure 34) should perhaps be made. First, Kormendy et al. (2009) have again introduced an apparent gap in their diagram by using only 9 galaxies from Binggeli et al.'s (1985) Virgo galaxy catalog within the magnitude range $M_V = -19 \pm 1$ mag. Obviously other elliptical galaxies exist with magnitudes over this range, and the HST data in Faber et al. (1997, their figure 4c) reveals that these 'gap galaxies' — which they identify as "power-law galaxies" — extend the linear $M - \mu_0$ relation defined by the dwarf elliptical galaxies (e.g. Jerjen & Binggeli 1997, their figure 3). Faber et al. (1997) did note that these galaxies may have dense, unresolved nuclear components which might increase their central surface brightness and erase this connection. However, the central surface brightness of the Sérsic model describing the host galaxy is not significantly different from that shown in their figure, and as such their speculation, which may be valid, is not actually relevant here as we are interested in the host galaxy unbiased by additional nuclear components.

The second issue regarding Kormendy et al.'s (2009) M–μ_0 diagram is that they have included M32, NGC 4486B plus 4 other "compact elliptical" galaxies fainter than $M_V = -17$ mag (VCC 1199, VCC 1627, VCC 1440 and VCC 1192; see Binggeli et al. 1985, their Table XIII). They claim that these objects, rather than the non-compact elliptical galaxies without partially depleted cores, define the faint-end of the elliptical galaxy sequence. Compact elliptical galaxies were once thought to be small elliptical galaxies because a quarter of a century ago they were thought to have $R^{1/4}$-like light profiles, just as the bright elliptical galaxies were once thought to have. However the bulge-disc nature of M32, the prototype "compact elliptical" which resides close to M31, reveals that it is likely a stripped S0 galaxy (Nieto 1990; Bekki 2001; Graham 2002) as does the age of its stellar population (Davidge et al. 2008).[20] Further analysis of other nearby"compact elliptical" galaxies has re-affirmed their bulge/disc nature (e.g. Smith Castelli et al. 2008; Chilingarian et al. 2009; Price et al. 2009; Huxor et al. 2011). Performing an anlaysis based on CCD data (Graham 2002), rather than the old photographic data used in Kormendy et al. (2009), to define the outer light profile of M32 results in parameters which do not position it at the extension of the core-galaxy distribution in the M–μ_0 diagram.

From the light profile data for VCC 1199 (Kormendy et al. 2009, their figure 24), a galaxy with the bright companion M49, one can see the bulge/disc transition at 5 arcseconds in the position angle, ellipticity and colour profiles. From the light profile data for VCC 1627 (Kormendy et al. 2009, their figure 24), one can again see a transition in the position angle and ellipticity profiles, while the colour profile has been truncated. The significant ordered structure in their data minus Sérsic model residual profile reveals the mismatched inner profile shape (evident as the hump out to 13 arcseconds) followed by excess light out to 28 arcseconds. This behaviour is

[20] We speculate that some old, 'free-flying' "compact elliptical" galaxies may be the descendants of the compact galaxies seen at $1.5 < z < 2.5$ which simply never accreted and built a significant cold disc (e.g. Kereš et al. 2005).

also displayed in the residual profile for VCC 1440, with a transition at about 6 arcseconds, where the ellipticity and position angle also change (Kormendy et al. 2009, their figure 23). Lastly, there is again clear evidence of this same structure in both VCC 1192's HST/ACS light profile (Kormendy et al. 2009, their figure 23), another galaxy which resides close to M49, and in NGC 4486B's light profile (Kormendy et al. 2009, their figure 22), a galaxy which resides close to M87. All of this is suggestive of a bulge/disc nature for these additional "compact elliptical" galaxies.

3.3.2. Luminosity-colour relation

Additional support for the dry merging scenario at the high-mass end is the flattening of the colour-magnitude relation above 0.5-1$\times10^{11}M_{\odot}$. While low luminosity, low Sérsic index, elliptical galaxies are bluer than bright elliptical galaxies (e.g. de Vaucouleurs 1961; Webb 1964; Sandage 1972; Caldwell & Bothun 1987), the brightest galaxies have the same colour as each other. This flattening in the colour-magnitude relation was noted by Tremonti et al. (2004) and is evident in Baldry et al. (2004, their Figure 9), Ferrarese et al. (2006a, their Figure 123), Boselli et al. (2008, their Figure 7) and even Metcalfe, Godwin & Peach (1994). These observations help alleviate past tension with semi-analytic models that had predicted a relatively flat colour-magnitude relation for bright elliptical galaxies (e.g. Cole et al. 2000). Previously, based on what was thought to be a linear colour-magnitude relation, Bernardi et al. (2007) had written that "if BCGs formed from dry mergers, then BCG progenitors must have been red for their magnitudes, suggesting that they hosted older stellar populations than is typical for their luminosities". However, the flattening in the colour-magnitude relation has since been recognised in yet more data sets (e.g. Skelton, Bell & Somerville 2009; Jiménez et al. 2011) although it should perhaps be noted that Skelton et al. reported the transition at $M_R = -21$ mag, i.e. $\sim$1 mag fainter.

In passing it is noted that the relation between luminosity and supermassive black hole mass (Marconi & Hunt 2003; McLure & Dunlop 2004) was found to be, after several refinements by Graham (2007), a linear one-to-one relation for black hole masses predominantly greater than $10^8 M_{\odot}$ — consistent with the concept of dry galaxy merging at this high-mass end.

3.3.3. Dynamics

From a sample of 13 early-type galaxies, plus one spiral galaxy, Minkowski (1962) noted that a "correlation between velocity dispersion and [luminosity] exists, but it is poor". He wrote that "it seems important to extend the observations to more objects, especially at low and medium absolute magnitudes". This was done by Morton & Chevalier (1973) who noted the same "continuous distribution of dispersions from 60 km/s for M32 to 490 km/s for M87" but also did not attempt to quantify this trend. It was Faber & Jackson (1976) who, with improved data and a larger sample of 25 galaxies, were the first to quantify Minkowski's relation and discovered that $L \propto \sigma^4$ for their data set. This result has proved extremely popular and is known as the Faber-Jackson relation. Not long after this, Schechter (1980) and Malumuth & Kirshner (1981) revealed that the luminous elliptical galaxies followed a relation with an exponent of $\sim$5 rather than 4. At the same time, Tonry (1981) revealed that expanding the sample to include more faint elliptical galaxies results in an exponent of $\sim$3. This led Binney (1982) to write that "probably the correlation cannot be adequately fitted by a single power law over the full range of absolute magnitudes" and Farouki et al. (1983) wrote that "the data suggests the presence of curvature in the $L-\sigma$ relation". Davies et al. (1983), and later Held et al. (1992), revealed that the dwarf elliptical galaxies followed a relation with an exponent of $\sim$2, which explains why Tonry (1981) had found a slope of $\sim$3 when including dwarf and ordinary elliptical galaxies. The relation found by Davies et al., with a slope of $\sim$2, has recently been observed by de Rijcke et al. (2005) and the curved or possibly broken $L-\sigma$ distribution has been interpreted by Matković & Guzmán (2005) as a change in slope at -20.5 B-mag (see also Evstigneeva et al. 2007) in agreement with Davies et al. (1983).

In spite of all the above work, there is a huge body of literature today which appears unaware that the $L-\sigma$ relation is curved or broken. Simulations of galaxies which succeed in producing the linear Faber-Jackson relation, $L \propto \sigma^4$, have actually failed to produce the full distribution of dynamics seen in real elliptical galaxies as a function of magnitude.

4. Disc Galaxy Light Profiles

The term "disc galaxy" refers to galaxies with large-scale stellar discs, encompassing both spiral (Sp) and lenticular (S0) galaxies, with the latter not displaying a noticeable spiral pattern of stars nor ongoing star formation — at least not in the optical (Gil de Paz et al. 2007). Broadly, their bulges are centrally-located stellar distributions with a smooth appearance, which appears as an excess, *a bulge*, relative to the inward extrapolation of the outer exponential disc light (excluding bars, nuclear star clusters and nuclear discs). Readers may like to refer to Wyse et al. (1997) for a fuller definition.

It is perhaps worth noting that as galaxy photometry and image analysis has improved over the years, along with the availability of kinematic information, it has become increasingly apparent that some galaxies previously labelled as elliptical galaxies actually possess a large-scale stellar disc and are in fact lenticular galaxies (Davies et al. 1983; Bender et al. 1988; Rix & White 1990). These have long been known to occur among the fainter early-type galaxies, rather than the massive elliptical galaxies (e.g. Liller 1960, 1966). Similarly, albeit to a lesser extent, some previously classified dwarf elliptical (dE) galaxies have also been recognised to contain a large-scale stellar disc and are therefore actually dwarf lenticular (dS0), and rarely dwarf spiral (dSp), galaxies (e.g. Graham & Guzmán 2003; Lisker et al. 2006a). To accurately quantify the optical structure of these, and all, disc galaxies, requires, as a minimum, that one models the 3D-bulge (when present) and the flattened 2D-disc as distinct entities rather than fitting a single $R^{1/n}$, or worse still $R^{1/4}$, model to both components.

The following section reviews the decomposition of disc galaxy light into its two primary (bulge and disc) components. A brief discussion regarding the problems of dust is provided in section 4.2, while a discussion of the problems with the identification of pseudobulges is presented in section 4.3. A few words about bulgeless galaxies are provided in section 4.4 while a number of references to works which have advanced the modelling, and shown the importance, of bars is provided in section 4.5. Those interested in the more detailed morphology and components of disc galaxies may like to look at R.Buta's Chapter in this volume.

4.1. The Bulge-Disc Decomposition

It has long been known that the (azimuthally averaged) radial distribution of star light in discs (i.e. the disc component of disc galaxies) can be reasonably well approximated with an exponential model (e.g. Patterson 1940; de Vaucouleurs 1957; 1958; Freeman 1970), such that the intensity I varies with R according to the expression

$$I(R) = I_0\, e^{-R/h}, \tag{18}$$

where I_0 is the central intensity and h is the e-folding disc scale-length. Expression relating these two quantities to the parameters of the Sérsic $R^{1/n}$ model, which reproduces an exponential model when $n = 1$, can be found in Graham & Driver (2005).

While the intensity profiles of these discs decline with radius, uninterrupted in most galaxies (e.g. Barton & Thompson 1997; Weiner et al. 2001; Bland-Hawthorn et al. 2005), deviations from this general exponential disc structure have also been known for a long time. Spiral arms can introduce bumps and upturns in the light profile, as seen in the data from de Jong & van der Kruit (1994) and highlighted by Erwin, Beckman & Pohlen (2005). On the other hand, some discs are known to partially truncate at a few disc scale-lengths (van der Kruit 1987; Pohlen et al. 2004, and references therein), including our own (Minniti et al. 2011), often resulting in an apparent double disc structure (van der Kruit 1979; van der Kruit & Searle 1981). Due to the non-zero thickness of discs, one can additionally study their vertical structure orthogonal to the plane of the disc (van der Kruit & Searle 1981; van der Kruit 1988; de Grijs et al. 1997; Qu et al. 2011, and references therein). Although it has been recognised that some galaxies may have both a thin and a thick disc (Gilmore & Reid 1983; Chang et al. 2011), the level of observational detail in most galaxies makes this separation impossible, and as such it is not common practice to attempt this differentiation in external galaxies.

Around the time of Capaccioli's (1985, 1989) advocation of Sérsic's $R^{1/n}$ model, Shaw & Gilmore (1989) and Wainscoat et al. (1989) remarked that the bulge component of spiral galaxies are neither all similar nor are they adequately described by the $R^{1/4}$ model. This was not a new result, as de Vaucouleurs (1959) had himself noted departures from the $R^{1/4}$ model, and van Houten (1961) had clearly demonstrated that an exponential model provided a better fit to some bulges than the $R^{1/4}$ model (see also, for example: Liller 1966, his figure 2; Frankston & Schild 1976; Spinrad et al. 1978). The exponential model was also eventually shown to provide a good description for the bulge of the Milky Way (Kent, Dame & Fazio 1991). While Andredakis & Sanders (1994) revealed that many bulges are better fit with an exponential model than an $R^{1/4}$ model, it was Andredakis, Peletier & Balcells (1995) who demonstrated that Sérsic's $R^{1/n}$ model provided a good description for the bulges of all disc galaxies. They discovered that the concentration of stars in bulges, quantified by the Sérsic index n, varied with bulge mass. After a number of other early works by Heraudeau & Simien (1997), Iodice, D'Onofrio, & Capaccioli (1997, 1999) Schwarzkopf & Dettmar (1997), Seigar & James (1998) and Wadadekar et al. (1999), it has become common practice to routinely fit disc galaxies with a Sérsic-bulge plus an exponential disc. Typical bulge Sérsic indices and bulge-to-disc flux ratios for spiral galaxies are provided in Table 1.

This Sérsic-bulge plus an exponential disc approach was used by Allen et al. (2006) to model over 10,000 galaxies from the Millennium Galaxy Catalog (Liske et al. 2003). From this, the luminosity function of bulges and discs, rather than simply galaxies, were constructed (Driver et al. 2007a). This is important because the spheroidal-bulge and flattened-disc component of galaxies formed through different physical processes. If one is to more fully understand the growth of galaxies, tracing their evolution in simulations or observing their evolution over a range of redshifts, then the disc galaxies should not be treated as single component systems. The stellar mass density of bulges and discs was subsequently derived by Driver et al. (2007a), superseding studies with a) notably smaller sample sizes and b) that had used $R^{1/4}$ models. A full correction for the obscuring effects of dust was provided by Driver et al. 2007b)

4.2. Dust and inclination corrections

The impact of interstellar dust[21] (see the review by Draine 2003) often does not receive the attention that it deserves. In addition to Trimble's (1999) scholarly report on how most studies from circa 1850 until Trumpler (1930a,b) ignored reports that the space between stars is not transparent, the influence of dust on modern, UV-optical and near-infrared measurements of the luminosity of bulges and discs is still to receive due diligence. This is not due to a complete lack of appreciation but rather because it is a difficult topic which has until recently been swept under the rug.

Although the importance and extent of dust's thermal *emission* at infrared wavelengths has been studied in external galaxies for over two decades (e.g. Devereux & Young 1990; Goudfrooij & de Jong 1995; Temi et al. 2004), the importance of dust *obscuration* at UV, optical and near-IR wavelengths has not fully filtered through to the entire community — even though it is primarily the reradiation of this absorbed energy which produces the infrared and millimetre wavelength emissions. It is hoped that the level of dust recognition may soon increase due to the vast interest and awareness in results from Spitzer (Werner et al. 2004) and coming from the infrared Herschel Space Observatory (Pilbratt et al. 2010; see also Walmsley et al. 2010) and also from the sub-mm Planck mission (e.g. Ade et al. 2011).

While most elliptical galaxies do not possess much diffuse dust (Bregman et al. 1998; Clemens et al. 2010), lenticular and spiral disc galaxies can have copious amounts (e.g. White et al. 2000; Keel & White 2001a,b). As a result, the far-side of a bulge viewed through the dusty disc component of a disc galaxy can have its light substantially diminished. Corrections for dimming due to dust, beyond the necessary masking in one's image when faced with obvious dust lanes and patches (e.g. Hawarden et al. 1981), therefore need to be applied to both the disc and bulge components of disc galaxies. To date, at optical wavelengths, these corrections have typically been inadequate for the disc and non-existent for the bulge (e.g. de Jong 1996; Graham 2001; Unterborn & Ryden 2009; Maller et al. 2009).

[21] Dust was formerly referred to as "dark matter" (e.g. Trumpler 1930a,b).

Table 1: K-band structural parameters for spiral galaxies, as a function of morphological type (Graham & Worley 2008). The median bulge Sérsic index is listed, along with the median bulge-to-disc size ratio R_e/h, and the median dust-corrected bulge-to-disc (B/D) luminosity ratio. The bulge-to-total (B/T) luminosity ratio can be obtained from the expression $B/T = [1 + (D/B)]^{-1}$. The range shown represents +/−34 per cent of the distribution about the median.

Type	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm
Sérsic n	$2.56^{+2.79}_{-0.79}$	$2.45^{+1.27}_{-0.75}$	$2.00^{+1.62}_{-0.76}$	$1.87^{+1.64}_{-0.75}$	$1.78^{+2.18}_{-0.79}$	$1.18^{+0.89}_{-0.49}$	$1.80^{+0.49}_{-1.22}$	$0.79^{+0.24}_{-0.13}$	$0.40^{+0.09}_{-0.09}$
R_e/h	$0.31^{+0.20}_{-0.17}$	$0.24^{+0.22}_{-0.10}$	$0.21^{+0.15}_{-0.07}$	$0.21^{+0.11}_{-0.09}$	$0.22^{+0.27}_{-0.09}$	$0.19^{+0.10}_{-0.06}$	$0.24^{+0.07}_{-0.10}$	$0.19^{+0.14}_{-0.07}$	$0.23^{+0.01}_{-0.01}$
$\log(B/D)$	$-0.34^{+0.40}_{-0.32}$	$-0.54^{+0.53}_{-0.41}$	$-0.60^{+0.28}_{-0.49}$	$-0.82^{+0.28}_{-0.42}$	$-1.06^{+0.43}_{-0.34}$	$-1.23^{+0.75}_{-0.28}$	$-1.06^{+0.16}_{-0.50}$	$-1.49^{+0.36}_{-0.36}$	$-1.57^{+0.01}_{-0.01}$

A simple schematic often used to help explain the influence of dust on discs is to start by considering an optically-thick, face-on disc in which you can only see some depth l into the disc before your view is obscured by dust. As this disc is inclined by some angle i, toward an edge-on orientation $i = 90\,\text{deg}$, your line-of-sight depth into (the z-direction of) the disc will be reduced by $\cos(i)$, and thus you will see even less stars, with the observed disc luminosity declining as the inclination increases toward an edge-on orientation. Numerous studies have revealed how the observed luminosity of disc galaxies declines with inclination (e.g. Tully et al. 1998; Masters et al. 2003). Correcting for this "inclination effect", in a sample average sense, yields the galaxy luminosities that would be observed if the inclined galaxies that one observed had a face-on orientation; and this is typically the only correction applied. However, after correcting to a face-on orientation, i.e. after determining the amount of flux one would observe if the disc galaxies were seen face-on, one still needs to apply an additional correction to determine the luminosity that would be observed from the face-on disc galaxies if the dust was not present. To date, most observational studies have only calibrated disc galaxy magnitudes to the face-on orientation; they have not then accounted for the obscuring dust which remains. To do so requires recourse to sophisticated radiative transfer models.

One such model is that from Popescu et al. (2000, 2011) which self-consistently explains the UV/optical/FIR/sub-mm emission from galaxies. Other recent radiative transfer codes which readers may find helpful include TRADING (Bianchi 2008), GRASIL (Schurer et al. 2009) and SUNRISE (Jonsson 2006; Jonsson, Groves & Cox 2010). Using these models, a renaisance of sorts is slowly starting to emerge in regard to correcting the optical, and near-infrared, luminosities of disc galaxies. Expressions are now available to fully correct for dust extinction in disc galaxies (e.g. Driver et al. 2008; Graham & Worley 2008). Such equations will become more refined as dust corrections for different disc morphological types, or luminosity, eventually become available.

Properly accounting for dust at ultraviolet, optical, and near-infrared wavelengths will have many ramifications. For example, the dust-corrected ultraviolet flux density in the local Universe (Robotham & Driver 2011) is significantly greater than previously reported, as is the associated star formation rate (SFR) density which is now equal to $0.0312 \pm 0.0045\ h\, M_{\odot}\ \text{yr}^{-1}\ \text{Mpc}^{-3}$. We are also now in a position to construct dust-free Tully Fisher (1977) relations, rather than relations that are based on the luminosities of dusty galaxies corrected only to a face-on inclination. Observations of the redshift evolution of this dust correction remain unexplored. Until addressed, measurements of evolution in galaxy luminosities and luminosity functions remain somewhat limited, although see the simulations by Somerville et al. (2011). Finally, it is also noted that one should correct for inclination and face-on dust extinction if using (the increasingly popular) photometric measurements to estimate redshifts (e.g. Yip et al. 2011).

Correcting for dust in galaxies has revealed that the luminosity output of the (local) Universe, at visible wavelengths from starlight, is actually twice as bright as observed (Driver et al. 2008; see also Soifer & Neugebauer 1991). It has also enabled a more accurate estimate of the stellar mass density of bulges and discs in the Universe today (i.e. at $z = 0$), with Driver et al. (2007b) report-ing that $\rho_{\rm discs} = 4.4 \pm 0.6 \times 10^8\, hM_\odot$ Mpc^{-3} and $\rho_{\rm bulges} = 2.2 \pm 0.4 \times 10^8\, hM_\odot$ Mpc^{-3}, implying that 11.9±1.7 h per cent of the baryons in the universe (Salpeter-'lite' IMF) are in the form of stars, with ≈58 per cent in discs, ≈10 per cent in red elliptical galaxies, ≈29 per cent in classical bulges and the remainder in low luminosity blue spheroidal systems.

4.3. Pseudobulges

Pseudobulges are rather controversial, and the final section of Wyse et al. (1997) highlights many concerns. These exponential-like bulges, formed from disc material, were discussed at length in Hohl (1975, see his Figure 6) which covered results from N-body simulations of discs over the previous seven years (see also Bardeen 1975). While it has since been shown that such 'pseudobulges' can coexist with 'classical' bulges in the same galaxy (e.g. Norman et al. 1996; Erwin et al. 2003; Athanassoula 2005), pseudobulges remain difficult to identify (because, in part, we now know that classical bulges can also have exponential light profiles) and they bring to mind different classes of object for different authors. Even in our own galaxy there has been confusion as to whether a pseudobulge or a classical bulge exists (Babusiaux et al. 2010). Due to an increasing number of papers using questionable criteria to separate bulges into either a classical bulge or a pseudobulge bin, this section has been included. However, readers who may regard the identification of pseudobulges as pseudoscience at this time may wish to skip to the following subsection.

Pseudobulges are not thought to have formed from violent relaxation processes such as monolithic collapse, early rapid hierarchical merging, nor late-time merger events, nor are they thought to have formed from cluster harassment of disc and irregular galaxies: i.e. processes that may have built the elliptical galaxy sequence. Such processes give rise to what are termed "classical bulges". Pseudobulges — or discy bulges in the notation of Athanassoula (2005) — are comprised of, or built from, disc material through either secular evolutionary processes (Hohl 1975; Combes & Sanders 1981; Combes et al. 1990) or alternatively invoked by external triggers (Mihos & Hernquist 1994; Kannappan, Jansen & Barton 2004). Pseudobulges are supposed to rotate and have an exponential light profile, akin to the disc material from which they formed (Hohl & Zhang 1975; Kormendy 1982; Pfenniger 1993; Kormendy & Kennicutt 2004), although, as we shall see, such behavior does not confirm their existence.

For many years the bulges of disc galaxies were generally thought to resemble small elliptical galaxies displaying an $R^{1/4}$ light-profile (e.g. de Vaucouleurs 1958; Kormendy 1977a; Kent 1985; Kodaira, Watanabe, & Okamura 1986; Simien & de Vaucouleurs 1986). After Andredakis & Sanders' (1994) revelation that many bulges are better approximated with an exponential model, some studies, not ready to abandon the $R^{1/4}$ model, started to report on an apparent bulge dichotomy: classical $R^{1/4}$-bulges versus exponential-bulges allegedly built from the secular evolution of the disc. After the eventual recognition that a continuous range of bulge profile shapes and properties exist (e.g. Andredakis et al. 1995; Khosroshahi et al. 2000; Graham 2001; Möllenhoff & Heidt 2001; MacArthur et al. 2003), we have since seen the practice by some of dividing classical versus secular bulges upon whether their Sérsic index n has a value greater than or less than 2 (Kormendy & Kennicutt 2004; Fisher & Drory 2008).

Kormendy & Kennicutt (2004) advocate several additional criteria, which sometimes can be used and other times cannot, for identifying pseudobulges. Their first criteria is a flattened shape similar to a disc, which is arguably the best criteria in theory but often difficult to observe in practice. Kormendy & Kennicutt claim that the presence of an inner spiral pattern (or a nuclear bar) rules out the presence of a classical bulge. However spiral patterns (in discs) can apparently exist within classical bulges (Jerjen et al. 2000b; Thakur et al. 2009). Moreover, the existence of inner discs within elliptical galaxies (e.g. Rest et al. 2001; Tran et al. 2001) is evidence that a classical bulge may be present, surrounding the disc. Indeed Kormendy et al. (2005) reiterate past suggestions that secular growth within a classical bulge may explain such inner discs, a scenario further supported by Peletier et al. (2007). That is, rather than secular evolution within a disc building a pseudobulge, one may have the construction of a disc within a classical bulge. A third criteria from Kormendy & Kennicutt (2004) is that a boxy bulge in an edge-on galaxy rules out a classical bulge.

Williams et al. (2010) have however shown that boxy bulges, (previously) thought to be bars seen in projection (Combes & Sanders 1981), do not all display cylindrical rotation and that they can have stellar populations different to their disc, revealing the presence of a classical (and very boxy) bulge. As noted, Sérsic index and rotation, reflecting the results from Hohl (1975), are additionally offered as a tool by Kormendy & Kennicutt (2004) to separate pseudobulges from classical bulges, and these criteria are addressed separately below, along with a discussion of ages and structural scaling relations. The intention is not to argue that "pseudobulges" do not exist, only to raise awareness that there are substantial grounds to question their identification from certain selection criteria.

4.3.1. Sérsic index

It has been suggested that one can identify pseudobulges if they have a Sérsic index of 1, i.e. an exponential light profile, or more broadly if they have a Sérsic index less than 2 (Kormendy & Kennicutt 2004). Given that bulges with $R^{1/4}$-like profiles are now known to be relatively rare (Andredakis & Sanders 1994) even among early-type disc galaxies (Balcells et al. 2003), this approach is somewhat problematic as it would tend to identify the majority of bulges as pseudobulges based upon the 400+ bulge Sérsic indices tabulated by Graham & Worley (2008). Given the extent of galaxy merging predicted by hierarchical models, it seems unlikely that most disc galaxies have not experienced a merger event that has influenced their bulge. Below we provide a reasonable argument why use of the Sérsic index to identify pseudobulges is at best risky, and at worst highly inappropriate.

As we have seen in this article, elliptical galaxies display a continuum in numerous properties as a function of mass (see also Graham & Guzmán 2003; Côté et al. 2007, and references therein). One of these properties is the concentration of the radial distribution of stars, i.e. the shape of the light profile (e.g. Caon et al. 1993; Young & Currie 1994). The low-mass dwarf elliptical galaxies, not believed to have formed from the secular evolution, or perturbation, of a disc, have Sérsic indices around 1 to 2. Therefore, disc galaxy bulges with Sérsic indices $n < 2$ need not have formed via secular disc processes, although some may have. The bulge of the Milky Way is a good example where an exponential (Sérsic $n = 1$) model (Kent et al. 1991; Graham & Driver 2007) describes the light of what is a classical bulge (Babusiaux et al. 2010). Furthermore, while secular evolution is not proposed to build large bulges, like the one in the Sombrero galaxy, such big bulges display a continuum of profile shapes with ever smaller bulges, such that the Sérsic index decreases as the bulge luminosity decreases (Table 1), which has led many to speculate that a single unifying physical process is operating (e.g. Peletier & Balcells 1996b) or at least over-riding what has gone before.

Domínguez-Tenreiro et al. (1998) and Aguerri et al. (2001) have grown bulges from hierarchical simulations and minor merger events that have Sérsic indices from 1 to 2. Scannapieco et al. (2010) have also shown that classical bulges formed by mergers can have Sérsic indices less than 2. Although their gravitational softening length was only two to four times their bulge scale-lengths this is comparable to the situation that observers often deal with (e.g. de Jong 1996). By fitting simulated light profiles, Gadotti (2008) revealed that one can reliably measure the Sérsic index for bulges if their half-light radius is larger than just 80 per cent of the image's point-spread function's (PSF's) half width half maximum (HWHM).

4.3.2. Rotation

The identification of rotating bulges goes back a long time (e.g., Babcock 1938, 1939; Rubin, Ford & Kumar 1973; Pellet 1976; Bertola & Capaccioli 1977; Peterson 1978; Mebold et al. 1979). Early-type galaxies can also display significant rotation, albeit likely due to the presence of a disc (e.g. Davies et al. 1983; Graham et al. 1998; Emsellem et al. 2007, 2011; Krajnović et al. 2008). Due to the presence of a bar, as opposed to a pseudobulge, classical bulges can also appear to rotate (e.g. Babusiaux et al. 2010). Classical bulges can also be spun-up by a bar (Saha et al. 2011). To further complicate matters, simulations of merger events can result in rotating elliptical galaxies (Naab, Burkert & Hernquist 1999; Naab, Khochfar & Burkert 2006; González-García et al. 2009; Hoffman et al. 2009), and Bekki (2010) has shown that a rotating bulge can also be created by a merger event, and is thus not necessarily a sign of a pseudobulge built by secular evolution from disc material as typically assumed.

This is not to say that inner, rotationally flattened and supported discs do not masquerade as bulges (e.g. Erwin et al. 2003), only that rotation may not be a definitive sign of "bulges" built via secular disc processes.

4.3.3. Ages

The bulge of the Milky Way consists of an old stellar population (Rich & Origlia 2005; Zoccali et al. 2006) and has kinematics consistent with a pressure-supported system rather than a rotationally-supported system (Wyse & Gilmore 1995; Babusiaux et al. 2010). Contrary to classical bulges formed early on in the Universe, pseudobulges are thought to be young, built from disc material.

Using optical and near-infrared colours, Bothun & Gregg (1990) had argued that S0 galaxy discs were more than 5 Gyr younger than the bulges they host, affirming the previously held belief that bulges are akin to old elliptical galaxies (Renzini 1999). With refined measurements, and avoiding obvious dusty regions, Peletier & Balcells (1996a) discovered that the colour and age difference (assuming old populations with identical metallicities) between the bulge and disc from the same galaxy, in a sample of early-type disc galaxies, are much closer than had been realised, but still with the bulges older than their surrounding discs. Peletier et al. (1999) went on to conclude that the bulges of their S0-Sb galaxies are indeed old and cannot have formed by secular evolution[22] more recently than $z = 3$ (see also Goudfrooij, Gorgas & Jablonka 1999 and Bell & de Jong 2000). From a sample of 9 late-type galaxies, Carollo et al. (2007) used optical and near-infrared images to discover that roughly half of their bulges were old and half were young (see also Gadotti & Anjos 2001).

Dust and bright young blue stars ($\lesssim$1 Gyr) can significantly bias the light at optical wavelengths (MacArthur et al. 2010), as can youngish ($\lesssim$2 Gyr) stars in the near-infrared due to thermally pulsing asymptotic giant branch stars (e.g. Freeman 2004; Tonini et al. 2010). From a line strength analysis Thomas & Davies (2006) concluded that secular evolution is not a dominant mechanism for Sbc and earlier type spirals, and Moorthy & Holtzman (2006) concluded that merging rather than secular evolution is likely the dominant mechanism for bulge formation (see also Jablonka et al. 2007). MacArthur, González & Courteau (2009) revealed, also with spectra rather than colours, that bulges in both early- and late-type spiral galaxies, even those with Sérsic indices $n < 2$, have old mass-weighted ages, with less than 25 per cent by mass of the stars being young. Based on the bulge's stellar populations and stellar gradients (see also Fisher et al. 1996), they concluded that early-formation processes are common to all bulges and that secular processes or 'rejuvenated' star formation generally contributes minimally to the stellar mass budget, but has biased luminosity-weighted age estimates in the past. Such 'frostings' of young stars, or up to some 25 per cent, have misled some studies into missing the fact that the bulk of the stellar mass in (most) bulges is actually old.

4.3.4. Scaling relations

Following on from Figure 7 for elliptical galaxies, figures 11 reveals how the K-band magnitudes of nearly 400 bulges vary with a) Sérsic index and b) the central surface brightness (extrapolated from the Sérsic fit outside of the core). The data points have come from the compilation by Graham & Worley (2008). While the scatter is large, there is no evidence of a discontinuity between bulges with n greater than or less than 2. The following linear relations, shown in the figures, appear to roughly describe the distributions:

$$M_K = -7.5\log(n) - 20.0; \quad (19)$$
$$M_K = 0.6\mu_{0,K} - 29.7. \quad (20)$$

The curved relation shown in Figure 11c is not a fit but simply

$$M_K = 0.6(\mu_{e,K} - 1.086b) - 29.7, \quad (21)$$

where $b \approx 1.9992n - 0.3271$ and $n = 10^{-(20.0+M_K)/7.5}$. That is, the above two linear relations predict the

[22] Peletier et al. (1999) additionally observed three late-type spirals with blue colours indicative of a young luminosity-weighted age.

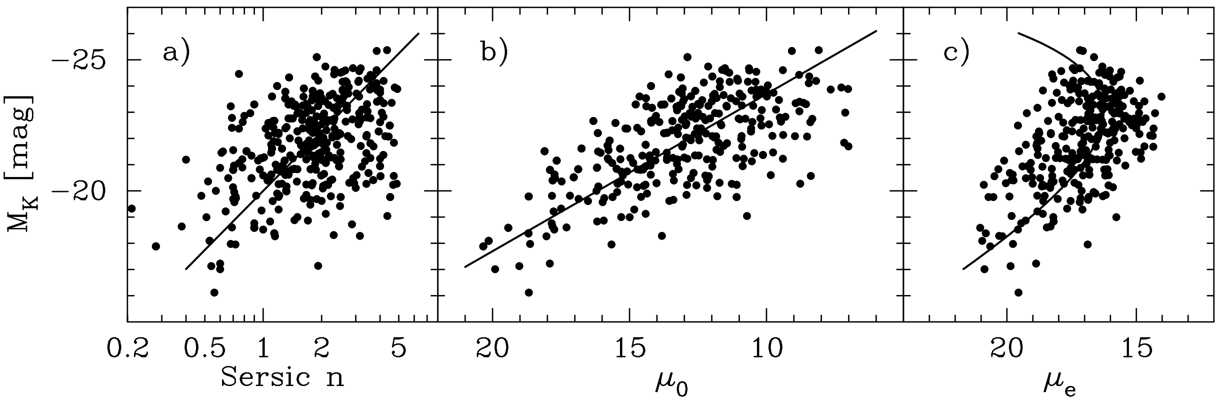

Fig. 11.— K-band bulge magnitude versus a) Sérsic index, b) central surface brightness (from the best-fitting Sérsic model) and c) effective surface brightness (compare Figure 8b). The data have come from the disc galaxy compilation by Graham & Worley (2008) and parameters were available for most bulges in each panel.

existence of this curved magnitude-(effective surface brightness) relation.

The scatter in the data, and the lack of bulges with $n > 4$, makes the curvature in Figure 11c hard to see with the current data. Instead, it may *appear* that there is a cascade of fainter data departing from the region associated with the bright-arm of the predicted relation corresponding to bulges with larger Sérsic indices. This apparent departure of fainter galaxies does not, however, imply that two physical processes must be operating.

Due to bulges possessing a continuous range of stellar concentrations, with their luminosity-dependent Sérsic indices n ranging from less than 1 to greater than 4 (Figure 11a), several bulge parameters will follow a number of non-linear scaling relations. The explanation for how this arises is provided in greater detail in section 3.2. Departures from the magnitude-(effective surface brightness) relation, the Kormendy (1977b) relation, and other relations including the Fundamental Plane (Djorgovski & Davis 1987), are expected at the low-luminosity, low Sérsic index, faint central surface brightnesses region of the bulge sequence. This does not imply that these bulges are pseudobulges (Greene, Ho & Barth 2008; Gadotti 2009), although some may be.

4.4. Bulgeless galaxies

The bulge-to-disc flux ratio, known to vary with disc morphological type (see Table 1) is primarily due to changes in the bulge luminosity along the spiral galaxy sequence, as first noted by Yoshizawa & Wakamatsu (1975, their figures 1 and 2) and reiterated by Ostriker (1977). Are there disc galaxies at the (small-bulge)-end of the sequence which actually have no bulge?

Although a central "bulge" in the light profile of the Triangulum nebula, M33, has long been evident (e.g. Stebbins & Whitford 1934, and references therein; van den Bergh 1991; Wyse et al. 1997), it has become common practice by many to nowadays refer to M33 as bulgeless. This is a reflection of efforts by some to try and distinguish some excesses of central light relative to the inward extrapolation of the outer exponential disc from a "classical" bulge of stars (e.g. Böker et al. 2003; Walcher et al. 2005). However some papers have even started referring to the Milky Way as bulgeless, because they feel that it may have a pseudobulge built from disc instabilities, and also labelling any galaxy whose bulge's Sérsic index is less than 2 as "pure disc" galaxies. As stressed by Cameron et al. (2009, their section 4), Allen et al. (2006) — who modelled over 10,000 galaxies with a Sérsic-bulge plus an exponential-disc — may have added to the confusion by referring to galaxies in which the bulge could not be resolved, and was thus simply ignored in the fit, as "pure disc" galaxies (see also Kautsch 2009a) rather than labelling them "quasi-bulgeless" as done by Barazza et al. (2008). Obviously the above practices have lead to quite a confusing situation in the literature today. Nonetheless, there are some good examples of what most would agree are almost truly bulgeless galaxies (free from either a classical or a pseudobulge), such as IC 5249 and NGC 300 with less than 2 percent bulge light (Bland-Hawthorn et al. 2005) and the superthin edge-on galaxies reviewed by Kautsch (2009b).

Current interest in bulgeless galaxies exists for at least two reasons. The first reason extends to disc galaxies with small bulges. Most galaxy simulations have, in the past, had a tendency to produce bulges rather than (pure) discs because of baryon angular momentum losses during major merger events (e.g. Navarro & Benz 1991; D'Onghia et al. 2006), and due to central star formation from minor merger events (Stewart et al. 2008). As highlighted by Graham & Worley (2008) and Weinzirl et al. (2009), many disc galaxies have small (<1/4) bulge-to-total flux ratios (see Table 1), which has been at odds with most simulations until recently (Koda et al. 2009; Governato et al. 2010; Brook et al. 2011; Fontanot et al. 2011)

The second reason pertains to claims of supermassive black holes (SMBHs) in bulgeless galaxies. Given the apparent wealth of data revealing correlations between the masses of supermassive black holes and the properties of their host bulge (e.g. Ferrarese & Ford 2006), the existence of supermassive black holes in bulgeless galaxies is an interesting unresolved problem. While the central kinematic data for the "bulgeless" galaxy M33 is consistent with no SMBH (Merritt et al. 2001; Gebhardt et al. 2001), SMBHs in allegedly bulgeless galaxies includes: NGC 4395 (Filippenko & Ho 2003, but see Graham 2007); NGC 1042 (Shields et al. 2008, but see Knapen et al. 2003); NGC 3621 (Gliozzi et al. 2009, but see Barth et al. 2009, their figure 4); NGC 3367 and NGC 4536 (McAlpine et al. 2011, but read their text and see Dong & De Robertis 2006). However, if the bulges of these "bulgeless" galaxies are pseudobulges, then questions arise as to the origin and connection of the SMBHs with these bulges. Given the connection between pseudobulges and bars (Hohl 1975), it is pertinent to perform bulge-bar-disc decompositions in galaxies with prominent bars, where the bar is perhaps still more connected to the disc instability than the ensuing pseudobulge (Graham 2011).

4.5. Barred galaxies

Disc galaxies can possess more components than just a bulge and disc; they may, for example, have bars, oval distortions and lenses, inner and outer rings, spiral arms, local star formation, etc. Interested readers may like to know that features arising from global instabilities in the disc are reviewed by J.Sellwood's Chapter in this volume. As was noted by the third galaxy reference catalog of de Vaucouleurs et al. (1991, and references therein), multiple components often exist, and sometimes these have been modelled (e.g. Tsikoudi 1979; Prieto et al. 1997, 2001). In addition to these large-scale features, nuclear bars and discs can also be present (e.g. de Zeeuw & Franx 1991; Rest et al. 2001), and when the resolution permits it, these can also be modelled (e.g. Balcells et al. 2007; Seth et al. 2008).

In this section we shall, however, only briefly discuss large-scale bars (reviewed by Knapen 2010, see also R.Buta's article in this volume). Roughly half to three-quarters of disc galaxies display a large-scale bar (e.g. de Vaucouleurs 1963; Eskridge et al. 2000; Marinova et al. 2011, and references therein) and many papers have performed a quantitative analysis of these (e.g. Martin 1995; de Jong 1996; Aguerri et al. 1998). Accounting for bars is important where these features are of sufficiently large amplitude to influence the models being fit to the light distribution (e.g., Laurikainen et al. 2005, 2007; Reese et al. 2007; Gadotti 2008; Weinzirl et al. 2009).

Ferrers' (1877) ellipsoid is often used to describe bars (e.g. Sellwood & Wilkinson 1993), as is Freeman's (1966) elliptical cylinder (e.g. de Jong 1996), generalised by Athanassoula et al. (1990). Sérsic's model is also sometimes used with $n = 0.5$, which reproduces a Gaussian function and has a sharpish decline at large radii for approximating the behavior seen at the ends of bars, although truncated models are also sometimes employed. While the bar shows up as a plateau in the galaxy light-profile corresponding to the bar's major-axis, in some galaxies the azimuthally averaged light-profile effectively recombines the bar and (apparently hollowed inner) disc light to reproduce an exponential profile, like that seen in the discs of non-barred galaxies (e.g. Ohta et al. 1990; Elmegreen et al. 1996).

The strength of a bar is often quantified by its ellipticity (e.g. Athanassoula 1992; Martin 1995; Wozniak et al. 1995) — a measure of the departure from the circular orbits of the disc stars — rather than its luminosity contrast (e.g. Ohta et al. 1990; Rozas et al. 1998). Strong bars have major-to-minor axis ratios of 3-4 while very strong bars may have ratios as high as 5. The gravitational torque has also been used to quantify bar strength (e.g. Combes & Sanders 1981; Laurikainen & Salo 2002) and similarly in triaxial bulges (e.g. Trujillo et al. 2002).

5. Summary

We have reviewed the progress over the last century in modelling the distribution of stars in elliptical galaxies, plus the bulges of lenticular and spiral galaxies and their surrounding discs. A number of nearly forgotten or poorly recognised references have been identified. The universality, or at least versatility, of Sérsic's $R^{1/n}$ model to describe bulges (section 4.1) and elliptical galaxies (section 2.1) extends to the stellar halos of cD galaxies (section 2.4) and simulated dark matter halos (section 2.1.1).

Dwarf and ordinary elliptical galaxies were shown in section 3.1 to be united by two continuous linear relations between absolute magnitude and a) the stellar concentration quantified through Sérsic's (1963) $R^{1/n}$ shape parameter (section 3.1.2), and b) the central surface brightness, which is also related to the central density (section 3.1.1). As discussed in section 3.3, a break in the latter relation at $M_B \approx -20.5$ mag signals the onset of partially depleted cores relative to the outer Sérsic profile in luminous elliptical galaxies. Additional scaling relations are also noted to show a change in character at this magnitude, which may denote the onset of dry galaxy merging.

The identification of depleted galaxy cores and excess nuclear light relative to the outer Sérsic profile was discussed in sections 2.2, 2.2.1 and 2.3. After accounting for these features, it was revealed how the above two linear relations result in curved scaling relations involving effective half light radii and effective surface brightness (section 3.2). Specifically, the M–$R_{\rm e}$, M–$\mu_{\rm e}$, M–$\langle\mu\rangle_{\rm e}$, $\mu_{\rm e}$–$R_{\rm e}$, $\langle\mu\rangle_{\rm e}$–$R_{\rm e}$ and n–$R_{\rm e}$ relations are non-linear. These continuous curved relations exist because elliptical galaxies do not have a universal profile shape, such as an $R^{1/4}$ profile, but instead a range of profile shapes that vary smoothly with absolute magnitude. Without an appreciation of the origin of these curved relations, they had in the past been heralded as evidence for a dichotomy between faint and bright elliptical galaxies. Numerical simulations and semi-numerical models which try to reproduce the full elliptical galaxy sequence must be able to reproduce these non-linear relations. This will likely require physical processes which work in tandem, albeit to different degrees over different mass ranges, to produce a continuum of galaxy properties that scale with mass while adhering to the linear M–n and M–μ_0 relations (subject to core-formation).

The structure of disc galaxies was reviewed in section 4, with section 4.1 covering the eventual recognition that bulges, like elliptical galaxies, are well described by the Sérsic model. A discussion of the difficulties in identifying pseudobulges was provided in section 4.3, covering the shape of bulge light profiles, rotation, stellar ages and non-linear scaling relations. Additional sections briefly encompassed issues related to dust (section 4.2), bulgeless galaxies (section 4.4) and models for barred galaxies (section 4.5).

The new 4 m Visible and Infrared Survey Telescope for Astronomy (VISTA, Emerson et al. 2004) and the upcoming 8.4 m Large Synoptic Survey Telescope (LSST, Tyson 2001) are expected to deliver sub-arcsecond, deep and wide field-of-view imaging covering thousands of resolvable galaxies. By pushing down the luminosity function into the dwarf galaxy regime, and through the application of improved galaxy parameterisation methods which allow for structural non-homology and the 2- or 3-component nature of disc galaxies, *both* statistical and systematic errors will be reduced. This will undoubtedly provide improved constraints on galaxy scaling relations and, in turn, a fuller understanding of galaxy evolution.

This research was supported under the Australian Research Council's Discovery Projects funding scheme (DP110103509). This research has made use of NASA's Astrophysics Data System (ADS) Bibliographic Services and the NASA/IPAC Extragalactic Database (NED).

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