THE MILLENNIUM GALAXY CATALOGUE: THE LUMINOSITY FUNCTIONS OF BULGES AND DISKS AND THEIR IMPLIED STELLAR MASS DENSITIES

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ABSTRACT

We derive the luminosity functions of elliptical galaxies, galaxy bulges, galaxy pseudobulges, and galaxy disks from our structural catalog of 10,095 galaxies. In addition, we compute their associated luminosity densities and stellar mass densities. We show that spheroidal systems (elliptical galaxies and the bulges of disk galaxies) exhibit a strong color bimodality indicating two distinct types of sphere that are separated by a core color of \( \mu - r \sim 2 \) mag. We argue that the similarity of the red elliptical and the red bulge luminosity functions supports our previous arguments that they share a common origin and surprisingly find that the same follows for the blue ellipticals and blue bulges, the latter of which we refer to as pseudobulges. In terms of the stellar mass budget we find that 58% \( \pm 6% \) is currently in the form of disks, 39% \( \pm 6% \) in the form of red spheroids (13% \( \pm 4% \) ellipticals, 26% \( \pm 4% \) bulges), and the remainder is in the form of blue spheroidal systems (~1.5% blue ellipticals and ~1.5% pseudobulges). In terms of galaxy formation we argue that our data on galaxy components strongly supports the notion of a two-stage formation process (spheroid first, disk later) but with the additional complexity of secular evolution occurring in quiescent disks, thus giving rise to two distinct bulge types: genuine “classical” bulges and pseudobulges. We therefore advocate that there are three significant structures underpinning galaxy evolution: classical spheroids (old), pseudobulges (young), and disks (intermediate). The luminous galaxy population is a mixture of these three structural types. The nature of the blue elliptical galaxies remains unclear, but one possibility is that these constitute recently collapsed structures supporting the notion of mass-dependent spheroid formation with redshift.

Subject headings: dust, extinction — galaxies: fundamental parameters — galaxies: photometry — galaxies: spiral — galaxies: structure

1. INTRODUCTION

In a recent paper (Driver et al. 2006) we demonstrated that galaxy bimodality is not just evident in color (see Strateva et al. 2001; Baldry et al. 2004) but also in the joint color-structure plane (see also Ball et al. 2006; Conselice 2006; Choi et al. 2007; Park et al. 2007). In that work we used Sloan Digital Sky Survey (SDSS) photometry and single Sérsic (1963; Graham & Driver 2005) profile fits to investigate the distribution of 10,095 relatively nearby luminous \( M_B < -17 \) mag) galaxies in the color-Sérsic index plane. The red peak is composed of highly concentrated, high-Sérsic index systems, while the blue peak contains more diffuse, low-Sérsic index systems. This is important as any movement from the blue peak to the red peak will require modifying the orbits, angular momentum, and energy of the entire stellar population. A simple inert process (e.g., exhaustion of the gas supply, stripping, etc.) could not achieve this, although a violent major merger event could (e.g., Barnes & Hernquist 1992). Perhaps more importantly, when the population was segregated by Hubble type we found that while the early-type galaxies (E/S0s, i.e., bulge-dominated) lay almost exclusively in the red-concentrated peak, and the late-type spirals (Sd/Ir, i.e., disk-dominated) in the blue-diffuse peak, the midtype spirals (Sabc, i.e., bulge plus disk systems) straddled both peaks with no obvious sign of bimodality. We inferred from this that galaxy bimodality arises because of the two-component nature of galaxies and that spheroidal structures (i.e., ellipticals and bulges) will lie exclusively in the red-compact peak and disks in the blue-diffuse peak. As classical bulges lie within thin rotating disk systems, this argues for early spheroid formation (via rapid merging or collapse) followed by a more quiescent phase in which the extended disk can form. To explore this further we have performed bulge-disk decomposition of all 10,095 galaxies in the Millennium Galaxy Catalogue (see Allen et al. 2006) by fitting two-component Sérsic-bulge plus exponential-disk models using GIM2D (Simard et al. 2002). In this Letter we report the luminosity functions derived for various component samples (e.g., ellipticals, bulges, disks) and tabulate the associated luminosity and stellar mass densities for each component class.

Throughout this Letter we assume a ΛCDM cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and we adopt \( h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) \) for ease of comparison with other results.

2. MGC COMPONENT LUMINOSITY FUNCTIONS

The Millennium Galaxy Catalogue (MGC) is a deep \( \mu_{17015} = 26 \) mag arcsec\(^{-2}\), wide area (37.5 deg\(^2\)), B-band imaging and redshift survey covering a 0.6 deg wide strip along the equatorial sky from 10 hr to 14 hr 50'. The MGC contains 10,095 galaxies down to \( B_{mgc} = 20 \) mag, of which 9696 have redshift information. Full details of the imaging survey can be found in Liske et al. (2003), with the spectroscopic follow-up described by Driver et al. (2005, hereafter D05). In Allen et al. (2006) the bulge-disk decompositions were reported for all 10,095 \( B_{mgc} < 20 \) mag galaxies, and a final structural catalog produced, consisting of bulge-only (Sérsic profiles), disk-only
(Sérsic or exponential profiles), and bulge plus disk systems (Sérsic plus exponential profiles).

Luminosity functions are computed using the standard stepwise maximum likelihood (SWML) estimator originally described by Efstathiou et al. (1988), with samples divided into bins of absolute magnitude. The MGC spectroscopic sample has a nominal Kron magnitude limit of $B_{\text{lim}} = 20$ mag. However, here we use the GIM2D total magnitudes (derived by integrating the light profiles to infinity) so that there is no longer a single limit that applies to the sample as a whole. To accommodate for this, each galaxy now has a unique magnitude limit, defined by $B_{\text{lim}} = 20 + B_{\text{mag}}$ (Sérsic) or $B_{\text{lim}}$ (Kron). Following D05, we restrict our sample to galaxies in the redshift range 0.013 < $z$ < 0.18 and within carefully defined size and surface brightness boundaries (see D05 and Liske et al. 2006 for full details).

2.1. $k+e$ Corrections

In D05 individual $k$-corrections were derived for each galaxy by comparing the total galaxy broadband colors ($uBgriz$) to the 27 spectral templates given in Poggianti (1998) and identifying the best-fitting spectrum. Having now separated the MGC galaxies into bulges and disks (see Allen et al. 2006), the global $k$-correction is not necessarily valid. However, approximately 50% of our sample are best fit by one-component profiles (i.e., bulge-only or disk-only galaxies), and for these systems we adopt the $k$-corrections as previously derived in D05. For the remaining two-component systems we consider our component colors too coarse to be used to derive robust individual $k$-corrections (as our decompositions are done in a single filter only). For the case of blue bulges and blue disks the global $k$-correction is likely to be appropriate for both (assuming that the blue bulge has formed from the disk). In the case of disks surrounding classical red bulges we note that for low-$B/T$ systems the $k$-correction is likely to be appropriate for the disks but not the bulges. In the case of high-$B/T$ systems we note that Peletier & Baccells (1996) report that such disks are typically redder. We therefore consider it appropriate to continue to adopt the global $k$-correction for both our disks and blue bulges. For the red bulges, however, we adopt the spectral template most frequently adopted by our single component red ellipticals (an Sa 15 Gyr spectrum). This spectrum can be represented by a fourth-order polynomial valid over the redshift range $0 < z < 0.18$ only:

$$k(z) = 3.86z + 12.13z^2 - 50.14z^3.$$  (1)

We note that if we follow a similar procedure for the disks and blue bulges the implied characteristic turnover luminosities (shown in Table 1) are systematically reduced by $\sim 0.1$ mag and the implied stellar masses reduced by $\sim 14\%$.

To model evolution we assume pure luminosity evolution of the following form:

$$L_{z=0} = L(1+z)^{-\beta},$$  (2)

where $\beta$ is set to 0.75 for the global luminosity function (see Driver et al. 2005), 1 for blue components (disks, blue bulges, blue ellipticals), and 0.5 for red components (red bulges and red ellipticals). These values are based on the recent results reported in Zucca et al. (2006) for red and blue systems (their types 1 and 4, respectively). We do not model number evolution as the redshift range is small and our merger rate estimates, based on dynamically close pairs within the MGC, are low (see De Propris et al. 2005, 2007).

2.2. Luminosity Functions

Figure 1 shows the luminosity distributions and Schechter function fits for our full galaxy sample (top left), ellipticals only (top right; i.e., objects with $B/T = 1$ after logical filtering, see Fig. 13 of Allen et al. 2006), disks (bottom left) and bulges (bottom right). Note that the Schechter function in the top left differs from that shown in D05 because the magnitudes are now based on Sérsic profiles integrated to infinity rather than Kron magnitudes. This difference is significant, resulting in a brighter $M^*$ value by about 0.1 mag but a comparable faint-end slope, $\alpha$. Analysis of independent repeat observations of $\sim 700$ galaxies suggests that our decompositions are valid to good accuracy ($\Delta M_{\text{bulge}} = 0.1$ mag and $\Delta M_{\text{disk}} = 0.15$ mag; see Allen et al. 2006) for components with luminosities with $M_b < -17$ mag. Below this limit our decompositions become increasingly less reliable, and these data are shown with open symbols. The most striking result from Figure 1 is the rapidly rising faint-end slope for the elliptical population. This was noted previously in Driver et al. (2006) and was shown to be due to contamination of the classical elliptical sample by low-luminosity blue spheroids (see also Ellis et al. 2005).

In Figure 2 we show the color-structure plane defined by the SDSS core ($u-r$) point-spread function color versus component Sérsic index for the ellipticals (top left) and galaxy bulges (top right). The bimodality of the ellipticals is striking, with a blue and red population being apparent. The blue sample defines what we label blue ellipticals, which were identified in
Ellis et al. (2005) and quantified in Driver et al. (2006). A cut at \((u - r) = 2\) mag provides a clear division. The bottom panels of Figure 2 show the luminosity distributions and Schechter function fits for the blue and red samples. We see that red and blue ellipticals follow markedly different trends, and it is indeed the blue ellipticals that are responsible for the apparent upturn in the total elliptical galaxy luminosity function at very faint absolute magnitudes. We note that when the bulges are divided in the same manner, the blue bulge luminosity function is very similar to that of the ellipticals, possibly indicating some common origin.

It is tempting to associate the blue bulges with pseudobulges (see Kormendy & Kennicutt 2004), which are believed to arise from inner disk instabilities giving rise to a “swelling” of the disk in the central region. As many of our blue bulges have \(M_b < -17\) mag, where our bulge-disk decompositions become unreliable, we cannot unambiguously confirm this population as pseudobulges but for the moment adopt this nomenclature for ease of discussion. The blue ellipticals remain somewhat intriguing and appear to define a new class of object as previously noted by Ellis et al. (2005) and Driver et al. (2006; see also Illbert et al. [2006], who identify them as a rapidly fading population). We are currently exploring these systems further (S. C. Ellis et al. 2007, in preparation) and for the moment simply flag them as interesting. From their distinct luminosity function it is clear they are predominantly low luminosity systems and could potentially represent the local counterparts to the luminous blue compact galaxies studied by Guzman et al. (1997) and Phillips et al. (1997).

Figure 3 shows the final component luminosity functions with the red ellipticals and red bulges combined into a single red spheroid group and the blue ellipticals and blue bulges...
grouped together into a single blue spheroid class. The justification for this is the similarity in the shapes and ranges of the luminosity distributions from Figure 2.

2.3. Luminosity Densities and Stellar-Mass Densities

Table 1 shows the Schechter function values for the luminosity function fits shown in Figures 1, 2, and 3, along with their associated $b_r$-band luminosity densities, $j_{b_r}$, and stellar mass densities, $\rho_M$. These are derived using the following expressions:

$$j_{b_r} = \phi \times 10^{-0.4(M_r - M_{M})} \Gamma(\alpha + 2)$$

and

$$\rho_M = \sum_{i}^{N} (\phi_i/N_i) 10^{(1.03(\alpha - r) - 0.79)} 10^{-0.4(M_{r} - M_{0})}.$$  \hspace{1cm} (4)

The latter expression was first shown in Driver et al. (2006) and is based on the color to mass-to-light ratios given by Bell & de Jong (2001), which assume a Salpeter-"lite" initial mass function. Note that the $(g - r)$ color for each galaxy was obtained by matching the MGC to the SDSS first data release (Abazajian et al. 2003).

3. DISCUSSION

Table 1 shows that 58% ± 6% of the stellar mass is in the form of galaxy disks, 13% ± 4% in red elliptical galaxies, and 26% ± 4% in classical red bulges. Previously it has been reported (Bell et al. 2003; Baldry et al. 2004; Driver et al. 2006) that 54%–60% of the stellar mass lies in the red peak dominated by early-type galaxies. As we have now separated the early-type galaxies into bulges and disks, one expects that the spheroid (elliptical+bulge) stellar mass density should be lower than the early-type stellar mass density, which of course includes the associated disk components of the lenticular galaxies.

Examining the color-structure plane (Fig. 2, top panels) for ellipticals and bulges we see that the red populations (of each type) lie in the same location. This is indicative of a shared origin for red ellipticals and classical red bulges. When combined the red spheroids account for 39% ± 6% of the stellar mass density. Hence the bulk of the stellar mass (97%) exists in the two classical structures originally defined by de Vaucouleurs (1959).

The remaining 3% lie in the form of blue ellipticals (~1.5%) and blue bulges (~1.5%). These latter two populations can therefore be considered minor from a cosmological perspective. Furthermore, as the blue bulges are likely to represent either difficulties in the decomposition (e.g., bars) or pseudobulges (disk swelling), their mass could arguably be added, in either case, to that of the galaxy disks (i.e., ~60%). The nature of the blue ellipticals (previously dubbed blue spheroids) remains uncertain, but they appear to constitute a very small fraction of the stellar mass budget; however, we must note the near-divergent faint-end slopes. The primary conclusion then is that the stellar mass is mainly divided between two distinct structures: blue two-dimensional disks and red three-dimensional spheroids.

Finally, we note that the results presented in this Letter are based on $B$-band data and therefore susceptible to dust attenuation (see Shao et al. 2006). Bell & de Jong (2001) argue that the effect on an individual galaxy’s stellar mass is less than one might expect (see their Fig. 1) because the observed decrease in total luminosity is offset by the increased stellar mass-to-light ratio inferred from the reddened colors, therefore yielding comparable final stellar masses. We explore this in detail in Driver et al. (2007) and note that while the masses are modified somewhat the final stellar mass breakdown is not dramatically altered.

The Millennium Galaxy Catalogue consists of imaging data from the Isaac Newton Telescope and spectroscopic data from the Anglo Australian Telescope, the ESO New Technology Telescope, the Telescopio Nazionale Galileo, and the Gemini Telescope. The survey has been supported through grants from the Particle Physics and Astronomy Research Council (UK) and the Australian Research Council (Australia). The data and data products are publicly available from http://www.eso.org/~jliske/mgc/ or on request from J. Liske or S. P. Driver.

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