

The Millennium Galaxy Catalogue: bulge–disc decomposition of 10 095 nearby galaxies

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ABSTRACT

We have modelled the light distribution in 10 095 galaxies from the Millennium Galaxy Catalogue (MGC), providing publicly available structural catalogues for a large, representative sample of galaxies in the local Universe. Three different models were used: (1) a single Sérsic function for the whole galaxy, (2) a bulge–disc decomposition model using a de Vaucouleurs ($R^{1/4}$) bulge plus exponential disc, (3) a bulge–disc decomposition model using a Sérsic ($R^{1/n}$) bulge plus exponential disc. Repeat observations for ~ 700 galaxies demonstrate that stable measurements can be obtained for object components with a half-light radius comparable to, or larger than, the seeing *half* width at half-maximum. We show that with careful quality control, robust measurements can be obtained for large samples such as the MGC. We use the catalogues to show that the galaxy colour bimodality is due to the two-component nature of galaxies (i.e. bulges and discs) and *not* due to two distinct galaxy populations. We conclude that understanding galaxy evolution demands the routine bulge–disc decomposition of the giant galaxy population at all redshifts.

Key words: astronomical data bases: miscellaneous – catalogues – galaxies: fundamental parameters – galaxies: general – galaxies: statistics – galaxies: structure.

1 INTRODUCTION

To understand the origins of the diverse galaxy population observed today, it is essential to quantify the properties of different structures which may be associated with separate formation processes. Recent work (e.g. Baldry et al. 2004) reported that the local Galaxy population consists of two distinct classes (red and blue). Driver et al. (2006) demonstrated that the galaxy bimodality is particularly distinct in the colour–log (n) plane, where n is the Sérsic index for the best-fitting $R^{1/n}$ model to the 2D galaxy light distribution. Furthermore, they suggested that the bimodality may be better interpreted as a representation of the two-component nature of galaxies (i.e. red bulges and blue discs). They arrived at this conclusion by noting that E/S0 and Sd/Irr galaxies lie in the two distinct peaks, whereas the Sabc galaxies (i.e. bulge+disc systems) straddle the two peaks. The colour bimodality may reflect the end-result of two different processes associated with bulge and disc formation.

It has long been known that although galaxies can cover an expanse of quite different morphologies, they have many prevalent

features in common, most notably spheroids (or bulges) and discs. The prominence of these features is often used to classify galaxies and place them into an evolutionary scenario (e.g. Hubble 1926; de Vaucouleurs 1959; van den Bergh 1976). Early classification of galaxy morphology was based on the visual inspection of images, and although this can be useful, significant differences between individual classifiers have been observed (e.g. Lahav et al. 1995; Naim et al. 1995a), and less-subjective techniques are clearly desirable.

In order to provide a more quantitative assessment of galaxy morphology, a number of different methods have been proposed and employed. For example, the concentration of the stellar distribution (e.g. Morgan 1958, 1959, 1962; Fraser 1972; de Vaucouleurs 1977; Graham, Trujillo & Caon 2001), along with its asymmetry in a C–A system (Burbidge, Burbidge & Crampin 1964; Elmegreen, Elmegreen & Montenegro 1992; Doi, Fukugita & Okamura 1993; Schade et al. 1995; Abraham et al. 1996) can be used to quantify galaxy morphology in a way that is not dependent on an assumed model. Extended classification systems also include a measure of the ‘clumpiness’ of the galaxy light (C–A–S; Conselice 2003). Other methods employ artificial neural networks (e.g. Naim et al. 1995b; Lahav et al. 1996; Odewahn et al. 1996) to classify galaxies according to a Hubble sequence scheme.

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Bulge–disc decomposition is another popular and useful method for quantifying the morphologies of galaxies by fitting model surface brightness profiles to data. Galaxies are described in terms of the two most easily recognized stellar components: bulges and discs. Such an approach has some clear disadvantages; the fitting process is model-dependent and does not account for secondary features such as spiral arms, rings, bars, star-forming knots, tidal tails, and other asymmetries. However, even at $z \sim 1$, bulges and discs are clearly in place and appear to be the dominant structural features in the majority of luminous ($M_B < -17$ mag) galaxies (e.g. Simard et al. 1999; Ravindranath et al. 2004; Barden et al. 2005; Koo et al. 2005; Trujillo et al. 2005). In addition, software is now available which makes it fairly straightforward to perform bulge–disc decomposition on many thousands of galaxies (e.g. Peng et al. 2002; Simard et al. 2002; de Souza, Gadotti & dos Anjos 2004; Trujillo & Aguerri 2004).

A bulge–disc model is also convenient because the surface brightness profiles of bulges are known to be well modelled by $R^{1/4}$ (de Vaucouleurs 1948), $R^{1/n}$, Sérsic (Sérsic 1968), or exponential laws (Andredakis & Sanders 1994; de Jong 1996a) and discs are observed to follow a pure exponential profile (de Vaucouleurs 1959; Freeman 1970). Bulges and discs are also often observed to have different average colours, metallicities, and kinematics, justifying their treatment as distinct entities. Most models of galaxy formation and evolution also involve separate formation scenarios for bulges and discs (e.g. Cole et al. 2000).

Using *Hubble Space Telescope* imaging, several statistically significant samples of high-redshift galaxies with measured structural parameters have been constructed (e.g. Simard et al. 2002; Ravindranath et al. 2004; Barden et al. 2005). However, for the local Universe, there only exist samples of hundreds of galaxies, that have had a bulge–disc decomposition, and these are often preselected to be only late type (e.g. de Jong 1996a; Graham & de Blok 2001; MacArthur, Courteau & Holtzman 2003), or early type (e.g. Caon, Capaccioli & D’Onofrio 1993; Graham & Guzmán 2003; de Jong et al. 2004), or in high-density environments (e.g. Gutiérrez et al. 2004; Christlein & Zabludoff 2005). In order to obtain a representative low-redshift sample, it is necessary to draw on a survey that is both deep and wide. Blanton et al. (2003) fitted a single Sérsic function to over 180 000 Sloan Digital Sky Survey (SDSS) galaxies, and recently Tasca & White (2005) have performed bulge–disc decomposition on a smaller sample of 1588 SDSS galaxies.

In this paper, we use a publicly available bulge–disc decomposition code (GIM2D; Simard et al. 2002) to provide a quantitative measure of the surface brightness profiles of 10 095 galaxies with $B_{\text{MGC}} < 20$ mag in the Millennium Galaxy Catalogue (MGC). In Section 2, we briefly describe the MGC data set analysed in this paper. Section 3 outlines the GIM2D fitting process. The resulting structural catalogues are introduced in Section 3.4, and in Sections 4, 5 and 6, we address the validity and repeatability of the structural measurements. Finally, in Section 7, we recover the fundamental empirical results describing bulges and discs [the Kormendy relation and the μ_0 –log(h) relation], and show that galaxy bimodality can be explained as a manifestation of distinct bulge and disc properties. In future papers, we use the structural catalogues presented in this paper to consider the bulge and disc luminosity functions (Allen et al., in preparation), the bulge–disc bivariate brightness and size distribution (Liske et al., in preparation), and the supermassive black hole mass function (Graham et al., in preparation). Throughout this paper, we assume a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and adopt $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ for ease of comparison with other results.

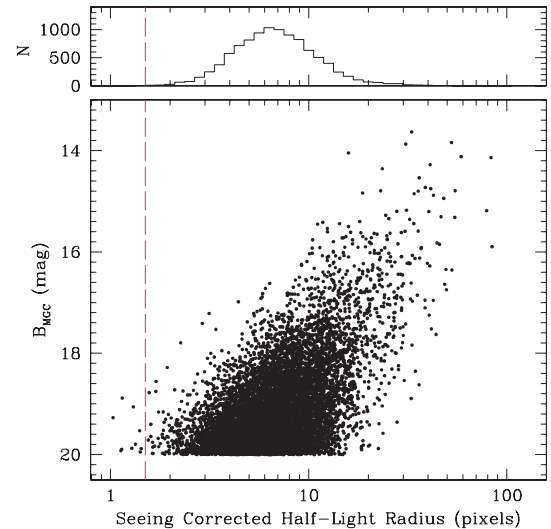


Figure 1. Seeing-corrected half-light radii (pixels) for MGC galaxies (as measured in Liske et al. 2003) versus apparent B -band magnitude. The dashed line shows the typical seeing HWHM. The pixel scale is 0.333 arcsec.

2 THE MILLENNIUM GALAXY CATALOGUE

The MGC¹ (Liske et al. 2003) is a deep ($\mu_{\text{lim}} = 26$ B mag arcsec⁻²), wide area (~ 37.5 deg²) imaging and redshift survey covering a 0.5 wide strip along the equatorial sky from 10^h to 14^h 50'. The survey region overlaps both the Two-degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), and the SDSS data release 1 (SDSS-DR1) (Abazajian et al. 2003). Comparison between these surveys shows that the MGC (which contains 10 095 galaxies with $B < 20$ mag) is deeper, more complete, more precise, and of higher resolution than either the 2dFGRS or SDSS-DR1 data sets (Cross et al. 2004; Driver et al. 2005). In Driver et al. (2005), their fig. 1 compares MGC imaging to Digitized Sky Survey (DSS) and SDSS imaging, and their fig. 3 demonstrates the extremely high redshift completeness of the MGC as a function of apparent magnitude, effective surface brightness, and colour.

Although the input MGC imaging is in the B band, a full match to the SDSS photometric catalogues provides additional colour information in the $ugriz$ bands. Full details of the MGC, including observations, data reduction, image detection and classification, are given in Liske et al. (2003). The MGC redshift survey is discussed in detail in Driver et al. (2005). With photometric precision of ± 0.03 mag, astrometric accuracy of ± 0.08 arcsec (Liske et al. 2003), and 96 per cent redshift completeness to $B_{\text{MGC}} = 20$ mag (increasing to 99.8 per cent for $B_{\text{MGC}} < 19$ mag), the MGC represents an extremely high quality and high completeness census of the local galaxy population. It is therefore the ideal data set to use for a detailed analysis of the structural composition of galaxies in the local Universe, and to provide a low-redshift anchor for higher redshift studies.

Fig. 1 shows the seeing-corrected half-light radii (as measured in Liske et al. 2003) for MGC galaxies as a function of apparent B -band magnitude. Most galaxies are intrinsically larger than the point spread function (PSF) half width at half-maximum (HWHM) and are therefore useful for structural analysis (NB: those galaxies that are much smaller than the typical PSF size are eventually removed from the final analysis – see Section 5.1).

¹<http://www.eso.org/~jliske/mgc>.

3 DECOMPOSITION OF GALAXY PROFILES

To perform 2D bulge–disc decomposition on the MGC sample, we elected to use the GIM2D package (Simard et al. 2002). GIM2D allows galaxies to be modelled using a single-component model, or a two-component bulge plus disc model. Where a two-component model is used, the components are required to have a common spatial centre, but their luminosities are independent, allowing the calculation of a bulge-to-total (B/T) luminosity ratio for each galaxy. The intensity profile of the spheroidal (bulge) components, $I_b(R)$, can be described using a Sérsic function (Sérsic 1968; Graham & Driver 2005):

$$I_b(R) = I_e \exp \left\{ -b_n \left[(R/R_e)^{1/n} - 1 \right] \right\}, \quad (1)$$

where the effective radius, R_e , encloses half the total bulge luminosity, and I_e is the intensity at the effective radius. The Sérsic parameter, n , determines the shape of the profile. A profile with $n = 4$ corresponds to the $R^{1/4}$ model (de Vaucouleurs 1948) that was traditionally used to describe bright elliptical galaxies. The term, b_n , is defined such that $\Gamma(2n) = 2\gamma(2n, b_n)$, where Γ is the complete gamma function and γ is the incomplete gamma function, ensuring that R_e encloses half the light for all values of n . The term b_n can be approximated by $1.9992n - 0.3271$ (Capaccioli 1989).²

For discs, the intensity profile, $I_d(R)$, can be modelled using an exponential function:

$$I_d(R) = I_0 \exp(-R/h), \quad (2)$$

where I_0 is the central intensity and h is the scalelength (identical to a Sérsic profile with $n = 1$). Although GIM2D permits the application of a simple opacity model for discs, we choose at this stage to treat discs as transparent and infinitely thin. We explore the effects of dust on disc opacity in a future paper (Allen et al., in preparation).

The ellipticity of the bulge component and the inclination of the disc component are permitted to vary independently. Flattening of bulges is described by an ellipticity, $\epsilon = 1 - b/a$, where a and b are the semimajor and semiminor axes of the ellipse, respectively. The bulge effective radius, and disc scalelengths computed by GIM2D correspond to the semimajor axes of the bulge and disc, respectively. Discs can have an inclination, i , from face-on ($i = 0$) to edge-on ($i = 90$), measured under the assumption that face-on discs are circular. Bulges and discs are also permitted to have independent position angles, θ_b and θ_d . Finally, the GIM2D code allows us to recalculate the background levels for each galaxy before the surface brightness models are fitted to the galaxies.

3.1 Galaxy input images and masks

Initially, GIM2D uses the SEXTRACTOR (Bertin & Arnouts 1996) output catalogue to prepare galaxies for analysis. In particular, the galaxy x – y position, sky background, and isophotal area as determined by SEXTRACTOR are required by GIM2D. Postage-stamp images were created for each galaxy, centred on the input x – y positions, with the height and width set to contain 10 times the SEXTRACTOR-determined isophotal area of the galaxy.

For each original image, SEXTRACTOR was set to produce a segmentation image, or mask. This consists of a pixel map defining

background pixels to have a value of 0, and pixels that are considered part of objects are assigned values of 1 to N . A mask postage-stamp image with the same dimensions as the input image was then produced for each galaxy. Fig. 2 shows example input MGC galaxies and their associated masks. In some cases, the masks did not distinguish between nearby objects (in most cases, two or more nearby objects were given the same pixel value in the mask). As we discuss later, this results in an erroneous output. When this occurred, SEXTRACTOR deblend and/or threshold parameters were changed to produce a correct mask (see Section 4.1 for full details) and the input masks remade.

3.2 Point spread functions

Before accurate profile measurements can be made, it is important to disentangle the intrinsic morphologies of galaxies from distortions that arise from the combined optical system of telescope, instrument, and atmosphere. These distortions vary both as a function of position and time, so their combined effects must be modelled using a PSF, which is unique to each galaxy. In the fitting process, GIM2D convolves the model profiles with a model PSF before comparing the model to the data.

Initially, the IRAF/DAOPHOT package was used to create a PSF model for each CCD frame. This was achieved using a minimum of 20 stars (often more), selected based on their SEXTRACTOR stellarity parameter being >0.8 , and their magnitude lying in the range $17 < B_{\text{MGC}} < 19.5$ mag. The stars were chosen to provide good spatial coverage of the CCD, to not be blended, to have no bright neighbours or saturated pixels, and to be away from CCD defects. The DAOPHOT routine PSF was then used to fit a model PSF for each CCD, based on the surface brightness profiles of the stars.

The PSF for each image was modelled using an analytic function, and a look-up table of residuals to account for the variation of the PSF across the CCD frame. The PENNY2 function, which consists of an elliptical Gaussian core with Lorentzian wings (both of which have independent position angles) was used to model the PSF, with the fitting radius of the function (i.e. the radius which encloses the region of pixels used in fitting the analytic function) defined to be equal to the median seeing for the frame, where the median seeing is the median full width at half-maximum (FWHM) of simple Gaussian fits to the profiles of stars. The diameter of the region used for fitting the PENNY2 function is therefore twice the estimated FWHM. The PENNY2 function consists of five free parameters, P_n (where $n = 1 \dots 5$), and a normalization factor, A , and can be expressed as:

$$\text{PENNY2} = A \times \left[\frac{1 - P_3}{1 + z} + P_3 \exp(-0.693e) \right], \quad (3)$$

where

$$z = \frac{x^2}{P_1^2} + \frac{y^2}{P_2^2} + xyP_5, \quad (4)$$

and

$$e = \frac{x^2}{P_1^2} + \frac{y^2}{P_2^2} + xyP_4. \quad (5)$$

The resulting PSF image is the best-fitting function to the light profile of the stars in the frame weighted by their signal-to-noise ratio.

To check the quality of the PSF, the ALLSTAR routine was used to reconstruct and subtract the PSF from the stellar images. When the PSF is good, the stars are cleanly removed from images leaving only sky noise. In most cases, the PSF provided a good model for the

²For $n < 0.36$, this approximation begins to fail (Ciotti & Bertin 1999), leading to uncertainties of the order of 0.1 mag arcsec^{−2} in surface brightness. Unfortunately, although more accurate functions are available (e.g. MacArthur et al. 2003), this approximation is a fixed feature of the GIM2D code.

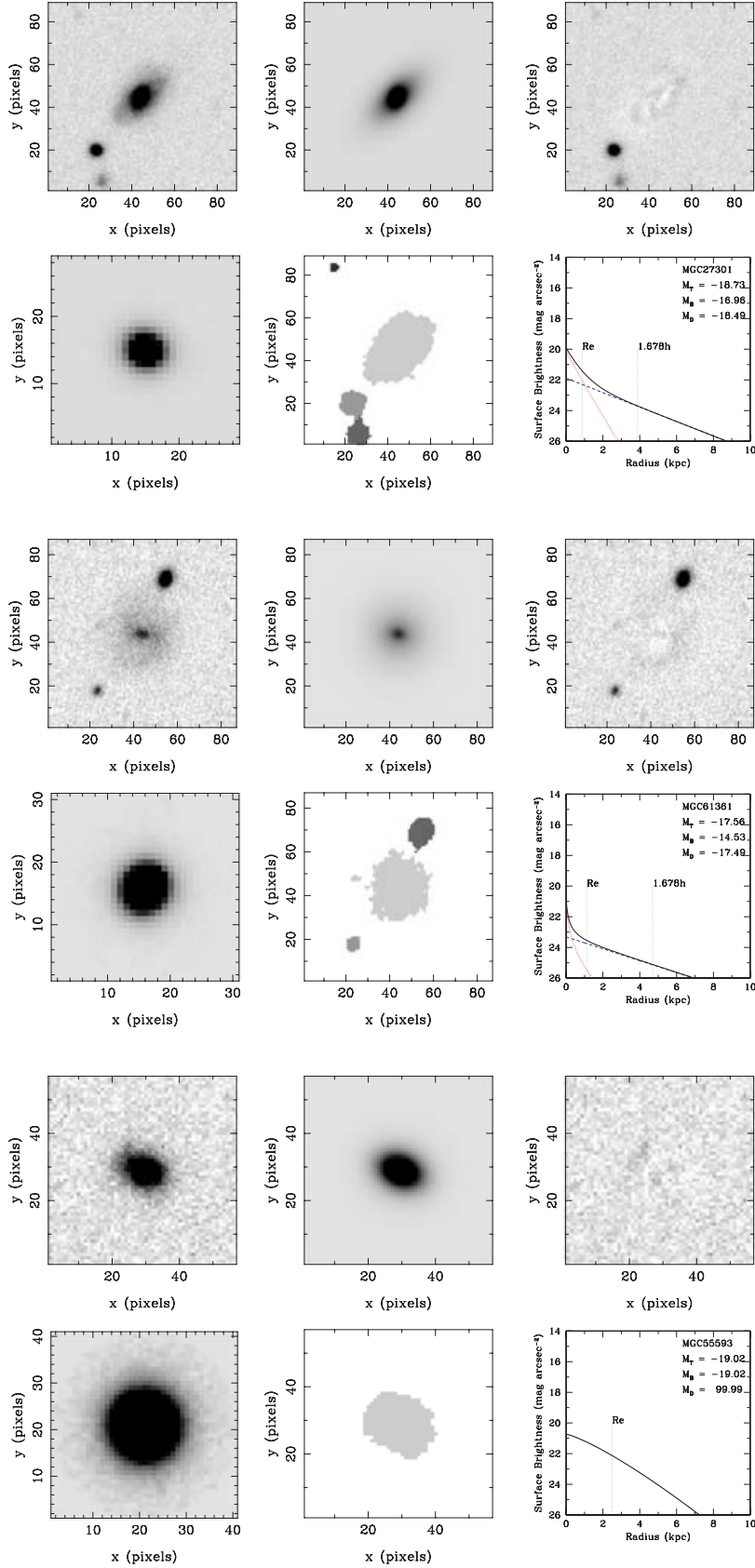


Figure 2. GIM2D input and output for three representative example galaxies: MGC 27301, MGC 61361 (both shown with Sérsic+exponential fits), and MGC 55593 (single-component Sérsic fit). For each galaxy, the top row contains images of the galaxy (left-hand panel), GIM2D model image (centre panel), and a residual image showing the difference (right-hand panel). The bottom row shows the input PSF (left-hand panel, note the expanded scale), the SExtractor segmentation image or mask (centre panel), and a plot of the best-fitting profile found by GIM2D (right-hand panel).

stars ($\chi^2_{\text{red}} \sim 1$, where χ^2_{red} is the reduced χ^2 for the fit), although for a small number of frames the χ^2_{red} values were poor and additional stars were rejected, and the PSF regenerated until an acceptable χ^2_{red} was obtained.

Using the model PSFs made for each CCD image, with the associated look-up tables, the DAOPHOT routine SEEPSF was employed to create an image of an artificial star corresponding to the exact location of every MGC galaxy. GIM2D then convolves this image with the model fits before comparison with the input data. Example PSF stars are shown in Fig. 2 (note the expanded scale for the PSFs).

3.3 The GIM2D models

Three different models were fitted to each MGC galaxy.

- (i) One component: fitted with a Sérsic function.
- (ii) Two components: de Vaucouleurs bulge + exponential disc.
- (iii) Two components: Sérsic bulge + exponential disc.

A full description of the GIM2D fitting algorithm is given in Simard et al. (2002), but a brief outline follows. The first stage in the fit is to further refine the background subtraction. GIM2D uses those pixels flagged in the SEXTRACTOR segmentation image as ‘background’ to estimate the mean value of the background. A 5-pixel buffer is placed around each object in the segmentation image to exclude possible object pixels from isophotes lower than the threshold that could potentially bias the background estimation. The new background value is then fixed, and 2D surface brightness fits are applied to the galaxies.

Table 1 shows the eight to 12 parameters that are fitted by GIM2D and the upper and lower limits permitted for each of the fits, most of which are based on GIM2D defaults. Since some galaxies are known to have $n > 4.0$ (e.g. Caon et al. 1993; Graham et al. 1996), we permit the Sérsic index to be as high as 12 (cf. Tasca & White 2005, who fixed $n_{\text{upper}} = 4$). Since we have assumed an infinitely thin disc, inclinations are given an upper limit of 85° . Bulge ellipticities are permitted to have a maximum value of 0.7. However, in the Sérsic-only catalogue, the fit may best correspond to either a bulge or a disc. Therefore, in this catalogue, those objects with a GIM2D upper error limit of 0.7 for the ellipticity were refitted using a revised upper limit

Table 1. The 12 parameters that can be fitted by GIM2D, and the upper and lower limits permitted in the fits. No entry indicates that no hard limits are applied. For the Sérsic-only (one component) fit, the B/T lower limit is constrained to 1.0, so only the Sérsic component is fit. When a de Vaucouleurs ($R^{1/4}$) fit is applied, the upper and lower limits of the Sérsic index are held fixed at $n = 4.0$.

Parameter		Lower	Upper
Total flux	F (counts)	0.0	–
Bulge/total flux ratio	B/T	0.0	1.0
Bulge effective radius	R_e (pixels)	0.0	–
Sérsic index	n	0.2	12.0
Bulge ellipticity	e	0.0	0.7
Bulge position angle	θ_b ($^\circ$)	–360.0	+360.0
Disc scalelength	h (pixels)	0.0	–
Disc inclination	i ($^\circ$)	0.0	85.0
Disc position angle	θ_d ($^\circ$)	–360.0	+360.0
x-position	Δx (pixels)	–	–
y-position	Δy (pixels)	–	–
Background level	Δb (counts)	–	–

of 0.92 (corresponding to an inclination of 85°), and both versions of the fit stored.

GIM2D uses the pixels flagged by the segmentation image as ‘object’ to measure image moments in order to produce initial estimates of the total flux, size, and position angle for each galaxy. Maximum values for these parameters are then set at twice the best estimates from the image moments. Using the limits applied in Table 1 and the maxima derived from the image moments, N models are created by coarsely sampling the permitted parameter space. For this analysis, we set $N = 400$. An ‘initial condition filter’ is then used to search through these models to find the best fit. The values associated with this model are then used as the starting point for the final fit. GIM2D then uses the METROPOLIS algorithm to search for the maximum-likelihood model (essentially a pixel-to-pixel χ^2 minimization) that best describes each galaxy. GIM2D also explores the parameter space around the best fit to compute 68 per cent confidence intervals for each parameter.

3.4 MGC structural catalogues

Publicly available MGC catalogues have already been released containing non-GIM2D parameters, such as photometry, imaging, estimates of galaxy half-light radii, mean effective surface brightnesses, and a match to SDSS-DR1 (Liske et al. 2003). These were supplemented with redshifts and rest-frame colours in Driver et al. (2005). The best-fitting values for the 12 parameters computed by GIM2D (see Table 1) have been combined with the MGC-BRIGHT catalogue (i.e. 10 095 galaxies with $B < 20$ mag) to produce three structural catalogues: one for each of the three models fitted here. For each fit, GIM2D also measures the reduced χ^2 (as computed between the PSF-convolved best-fitting model and the input data) as a measure of goodness-of-fit. Furthermore, using the topology of parameter space explored during the fitting process, GIM2D computes 68 per cent confidence limits for each of the parameters (see Simard et al. 2002). Although these errors are included in the catalogues, they only account for uncertainties in the formal fits. Uncertainties and errors due to the sky background and PSF, which can often dominate, are not considered in these estimates. This is discussed further in Section 6.

For each galaxy, in addition to the catalogue of structural parameters, output PSF-convolved model images, and residual images are also produced by GIM2D. Fig. 2 shows example output and residual images for three galaxies: MGC 27301, MGC 61361 and MGC 55593, along with the raw images, masks and PSFs, and a plot of the best-fitting profiles. Further details of our final catalogue parameters are made available at the MGC website (<http://www.eso.org/~jliske/mgc>).

3.4.1 Other parameters

After profile fitting has taken place and output and residual images made, GIM2D also computes several measures of concentration and asymmetry which are described in detail in Simard et al. (2002). These include the $C-A$ system (based on Abraham et al. 1996) and, using residual images, R_T and R_A (Schade et al. 1995). Two other measures, A_z and D_z , are also defined by Simard et al. (2002) as part of the GIM2D package. Although these parameters are not discussed further in this paper, the $C-A$ parameters are made available in the final MGC structural catalogues, and the other asymmetry measures are available on request.

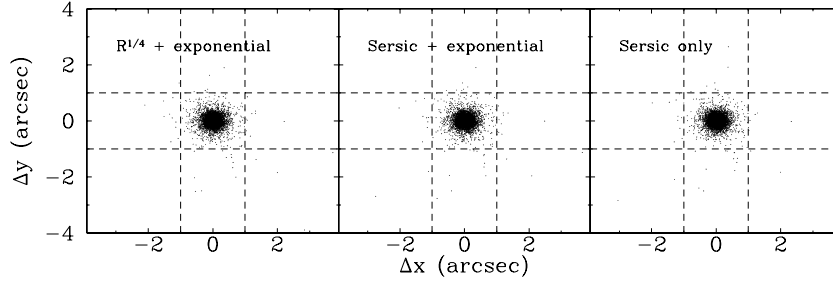


Figure 3. Residual offsets in the location of the object centre as determined by SEXTRACTOR and GIM2D (in x - y pixels), are shown for the de Vaucouleurs + exponential catalogue (left), the Sérsic + exponential catalogue (centre), and the single-component Sérsic catalogue (right). The dashed lines correspond to a difference of 3 pixels ($=1$ arcsec) in either x or y .

4 QUALITY CONTROL

4.1 Comparison with independent measurements

As an initial test on the accuracy of the GIM2D output, simple global observables such as magnitudes, half-light radii, and x - y centroid positions can be compared to their values measured using other means in the Liske et al. (2003) MGC catalogues. In most cases, the agreement is excellent, although there are a number of outliers, which can be a useful part of the quality-control process as we discuss in Section 4.2.

Fig. 3 shows the residuals between the SEXTRACTOR and GIM2D centroids. The majority of objects (88.0 per cent) lie within 1 pixel of the SEXTRACTOR central position, and 99.1 per cent have GIM2D central positions within 1 arcsec (3 pixels) of the SEXTRACTOR position for the Sérsic+exponential catalogues, and similar accuracy is found for the other two models used in this paper. In most cases, an outlying object is simply a sign of an irregular galaxy with an offset or ill-defined core, although it can, as we discuss in the next section, indicate problems with the masks (SEXTRACTOR segmentation images), or the GIM2D output.

Fig. 4 shows the difference between the Liske et al. (2003) and GIM2D magnitudes as a function of MGC magnitude, and the best-fitting relations between these parameters along with residual histograms, and the mean and standard deviation (with iterative 3σ clipping). For all three structural catalogues, the GIM2D magnitudes are brighter by 0.07–0.09 mag, with a 0.05–0.07 mag standard deviation. There appears to be no significant trend with magnitude. Systematically brighter GIM2D magnitudes are not unexpected since profiles are integrated to $R = \infty$, and it is known that flux can be missed when using aperture or Kron magnitudes (see Graham & Driver 2005). There are a small percentage of objects with large residuals that we discuss in the next section.

Finally, GIM2D also computes an *approximate* measure of the total galaxy half-light radius, which assumes that the bulge and disc have the same position angle (although the position angles are independent in the fits). In Fig. 5, the GIM2D galaxy half-light radii are compared to the seeing-corrected half-light radii measured in Liske et al. (2003). Again, there is good agreement but with some scatter. It is also notable that at small radii ($\lesssim 1.2$ arcsec) the GIM2D radii are smaller than the Liske et al. (2003) radii. This is unsurprising as it is in the regime where the PSF is of comparable angular size to the galaxies. GIM2D measurements will be dominated by errors due to the PSF correction and the original MGC measurements will be subject to the assumptions of the seeing correction applied by Liske et al. (2003). For larger, well-resolved galaxies, the GIM2D

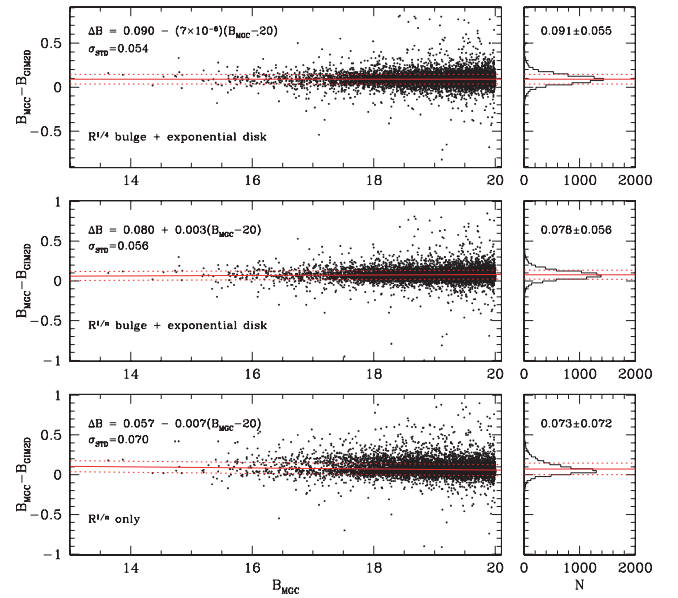


Figure 4. Differences between MGC galaxy magnitudes (determined by SEXTRACTOR) and GIM2D magnitudes, as a function of MGC magnitude. The solid line shows the least-squares fit to the data, and the dashed lines define the 1σ envelope. There is no apparent trend with magnitude. The GIM2D magnitudes are slightly brighter in all three catalogues: de Vaucouleurs+exponential (top panel), Sérsic+exponential (middle panel), and Sérsic (bottom panel). The panels on the right-hand side show histograms of the residuals. The mean and standard deviation (with 3σ clipping) of these distributions are shown in each case.

half-light radii are slightly larger, as expected, given their brighter magnitudes.

4.2 Reanalysis of outliers

Analysis of the input and GIM2D output images of outlying objects in Figs 3 and 4 reveals that the difference in parameters between Liske et al. (2003) and GIM2D measurements can have a number of sources. In some cases, galaxies are irregular, with more than one possible ‘centre’, or have a very asymmetric surface brightness distribution. The GIM2D models can be a poor fit to such objects, and position and magnitudes consequently have significant differences. In addition, many objects have nearby neighbours, in which case SEXTRACTOR has applied a deblending algorithm to attempt to separate the flux from the two objects. SEXTRACTOR creates a mask image with overlap

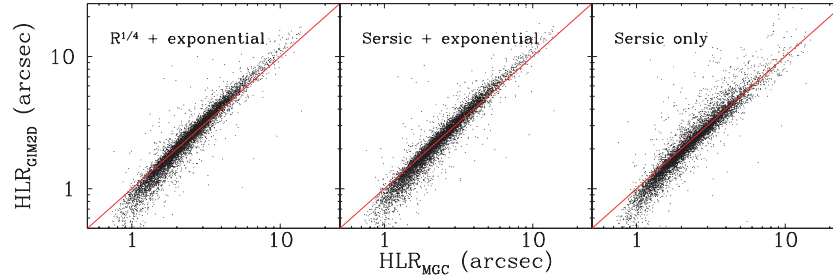


Figure 5. Comparison between galaxy half-light radii measured by GIM2D, and seeing-corrected half-light radii computed in Liske et al. (2003), for the de Vaucouleurs+exponential catalogue (left-hand panel), the Sérsic+exponential catalogue (centre panel), and the single-component Sérsic catalogue (right-hand panel). There is good agreement except at small radii where the PSF dominates.

pixels simply designated to one object or the other. However, when SEXTRACTOR computes the magnitudes for these objects, the flux in the pixels lying in overlap regions is shared between the two objects. No such deblending is performed by GIM2D, which simply uses the mask, and all the flux is assumed to belong to one object or the other. Therefore, some GIM2D inputs can be contaminated by light from nearby neighbours, and the derived magnitudes will differ from those determined by SEXTRACTOR.

Another cause of large parameter differences are erroneous masks or segmentation images. SEXTRACTOR, like most automated detection algorithms, is typically set to run with ‘optimal’ tuning (i.e. the detection parameters are set so that reasonable output is produced for as many objects as possible). Nevertheless, a fraction of objects at the extremes will still be incorrectly recovered. Perhaps, the best examples are the SEXTRACTOR-deblending parameters DEBLND_NTHRESH and DEBLND_MINCONT which govern the number of deblending thresholds, and the minimum contrast used when SEXTRACTOR decides whether two nearby local maxima in surface brightness are significant enough to be considered separate objects, or just structure within a single object. At one extreme, if the deblending is too strong, objects such as spiral discs or irregular galaxies can be broken up into several smaller objects. At the other extreme, two nearby, but clearly distinct objects are considered one, and assigned the same arbitrary pixel value in the mask (this is especially common when a small object lies close to a much larger one). To confuse matters further, in a small number of cases, SEXTRACTOR has failed to assign different pixel values to two nearby objects in the mask, even if two objects appear correctly deblended in the catalogue. These errors can be fixed by changing the deblend parameters to be more or less sensitive depending on the problem, and rerunning SEXTRACTOR. However, it is not possible, even using the most optimal setup, to produce output that is satisfactory in every case. This is a problem when trying to automate measurements for increasingly large data sets as it becomes more and more difficult to check all objects by eye (and defeats the purpose of trying to automate the process!). Either some fraction of wrong detections has to be tolerated, or a way needs to be found where the failures can be flagged and corrected.

For the MGC, all 10 095 objects were checked by eye in Liske et al. (2003) and, therefore, as already discussed, differences between the Liske et al. (2003) catalogues and GIM2D output can be indicative of bad masks. If a galaxy has been overdeblended, then the GIM2D magnitude will be an underestimate. When two galaxies are treated as one, the centroids will be grossly different, and the GIM2D magnitudes overestimated. All objects with Δx or Δy greater than 3 pixel (1 arcsec) or a magnitude difference $|\Delta B| > 0.2$ mag,

were selected and inputs, outputs, and masks examined by eye. It was found that 222 masks needed to be corrected by hand.

An example is shown in the top row of Fig. 6, with the original input image, bad mask (which assigns the same pixel value to two distinct objects), and the clearly erroneous GIM2D fit on the right. A corrected mask, which is produced by making small adjustments to SEXTRACTOR deblending and threshold parameters, is shown in the bottom panel, along with the (now corrected) GIM2D output.

5 INTERPRETING GIM2D OUTPUT

One of the problems with automatic bulge–disc decomposition routines is that in addition to perfectly good fits, they automatically generate a lot of rubbish. In this section, we describe our best efforts to clean up this situation.

As a starting point, we first trim the catalogue and examine only those systems within the redshift range $0.013 < z < 0.18$, and impose the galaxy size and surface brightness limits introduced in Driver et al. (2005). This results in a trimmed catalogue of 7750 galaxies (see Driver et al. 2005).

The interpretation of single-component Sérsic fits is fairly trivial, with the resulting light profile assumed to be the best fit to the light from the entire galaxy. However, when two components are modelled, the two functions are typically taken to correspond to a bulge and a disc. It is necessary to verify whether or not this is the case, ensuring that the two-component model really does correspond to two distinct structural components within a galaxy. This is especially important in the case where a Sérsic+exponential model is used because this fit has the most degrees of freedom.

No restrictions on the relative sizes of the ‘bulge’ and ‘disc’ components were applied when using GIM2D. The two components can sometimes be inverted or used to fit other structural features, especially in irregular galaxies. The component light profiles may also cross once, twice or not at all. To ensure the correct interpretation of the GIM2D fits (and whether components should be interpreted as bulges, discs, or something else), we classify all profiles into one of eight different types: six are composed of two components, and two have only single-component profiles. The two-component profile types are plotted in Fig. 7 for six example galaxies from the Sérsic + exponential catalogue. The profile types can be summarized as follows.

(i) *Type 1* ‘Classic’ profile. The Sérsic profile dominates at the centre, while the exponential profile dominates the flux at large radii. At a surface brightness brighter than $26 \text{ B mag arcsec}^{-2}$, the profiles

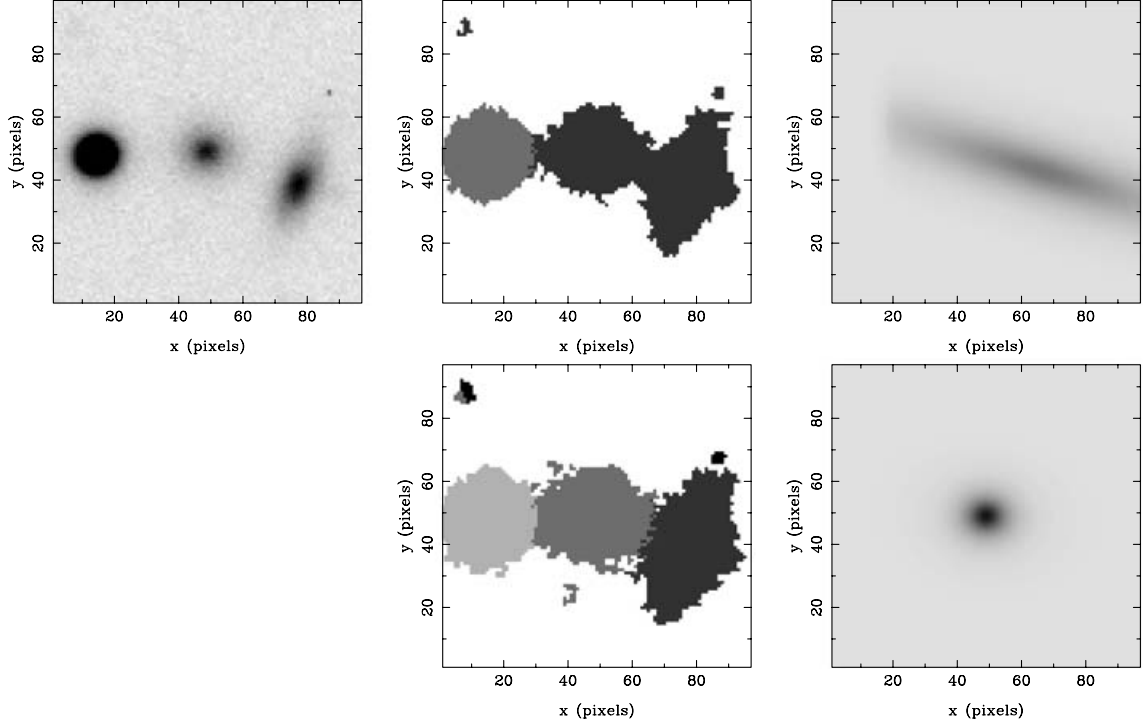


Figure 6. An example of bad and corrected mask images. The top left-hand panel shows the input image for MGC 64481 (the central object), and the original mask (top centre panel). The top right-hand side image is the original GIM2D output image, which can be initially identified due to its large centroid offset, and magnitude difference between the GIM2D output and Liske et al. (2003). The bottom panels show the corrected mask and output images.

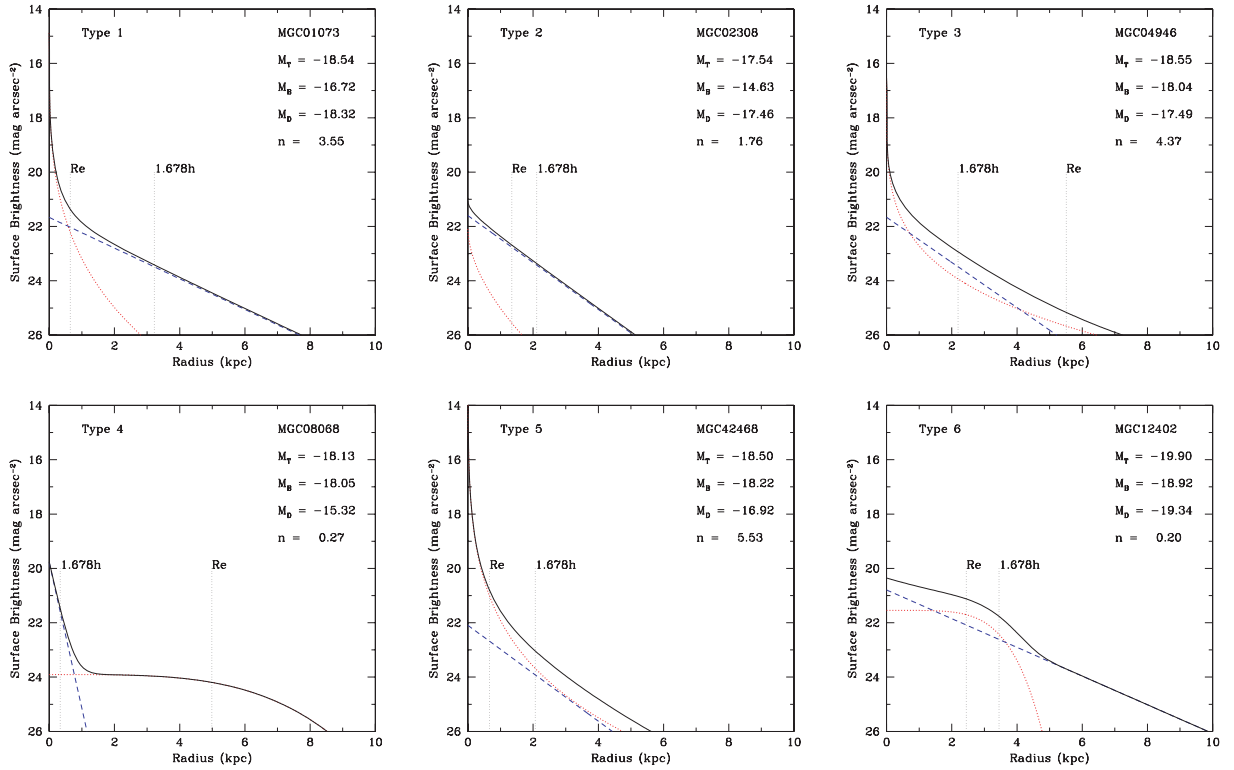


Figure 7. Example surface brightness profiles for the six distinct types of GIM2D fit that we use to classify galaxies from the Sérsic + exponential catalogue (see text). In each panel, the bold solid line represents the total profile, the Sérsic component is represented by a dotted curve, and the dashed straight line represents the exponential component. The locations of the half-light radii for each component: R_e , and $1.678 h$, are also shown. Table 2 summarizes the frequency with which each type occurs.

cross only once (i.e. they have the same surface brightness at only one radius).

(ii) *Type 2 Disc-dominated system.* The exponential profile dominates at all radii, with a small, central Sérsic profile. The profiles never cross, and B/T is always < 0.5 .

(iii) *Type 3 Sérsic profile.* It dominates at small and large radii, but an exponential profile dominates at intermediate radii. The profiles cross twice. B/T is always > 0.5 , and the Sérsic index, n is typically > 1.5 . Objects fitted by these profiles are typically single-component elliptical galaxies.

(iv) *Type 4 Inverted profile.* The exponential profile dominates at the centre, and the Sérsic profile dominates at large radii. The profiles cross only once, and n is always small. The correct interpretation of the profile is problematic, and could be a signature of possible disc truncation, poor background subtraction, or the profile could correspond to irregular or dwarf systems.

(v) *Type 5 Bulge or disc dominated.* The Sérsic profile dominates at all radii, with a weak underlying exponential component. The profiles never cross, and $B/T > 0.5$. There is a bimodal distribution in n for this type (see Section 5.1).

(vi) *Type 6 Disc with perturbation.* The exponential profile dominates at small and large radii, and the Sérsic profile briefly dominates at intermediate to large radii. The profiles cross twice. The Sérsic component models either a disc perturbation (such as a spiral arm), or features in an Irregular galaxy.

(vii) *Type 7 Pure disc.* An exponential-only profile with $B/T = 0$.

(viii) *Type 8 Pure bulge, disc, or other.* Sérsic profile only with $B/T = 1$. A bimodal distribution in n reveals discs with $n \sim 1$, and bulges with $n \sim 4$ for our sample.

All eight profile types occur in the Sérsic+exponential catalogue, types 1, 2, 3, 5, 7 and 8 occur in the de Vaucouleurs+exponential catalogue, and the Sérsic-only catalogue only contains type 8 profiles by definition. In both the Sérsic+exponential and the de Vaucouleurs+exponential catalogues, the majority of galaxies are of type 1. In the de Vaucouleurs+exponential catalogue, nearly a third of galaxies are best modelled by an exponential-only fit (type 7), three times as many as in the Sérsic+exponential catalogue. Table 2 summarizes the fraction of each type that is found in the three different catalogues.

5.1 The logical filter

The use of raw GIM2D profiles from the two-component models would clearly be inappropriate, given the distinct and often physically meaningless profiles that are fitted in some cases (e.g. types 4 or 6). Moreover, many systems do not actually exhibit two compo-

Table 2. The fraction of galaxies corresponding to each profile type (see Fig. 7).

Type	$R^{1/n}$ + exponential (per cent)	$R^{1/4}$ + exponential (per cent)	$R^{1/n}$ (per cent)
1	50.8	52.5	0
2	9.5	0.4	0
3	1.9	4.1	0
4	5.9	0	0
5	14.1	7.1	0
6	4.8	0	0
7	12.1	35.3	0
8	0.8	0.5	100

nents, and in these cases it is not surprising that a two-component fit produces erroneous output. A non-negligible fraction of incorrect output is typical for most automated algorithms. A quick inspection of the bulge–disc decompositions from BUDDA (de Souza et al. 2004), and Aguerri et al. (2005) reveal that problems with automatic decompositions are pandemic, with many fits having unrealistic bulge-to-disc size ratios, disc components clearly falling faint of the outer discs in spiral galaxies, and bulge flux dominating at large radii in late-type spiral galaxies, etc. While automatic codes find the optimal mathematical solution, perturbations in the real data from the fitted models often result in the mathematical solution being an unphysical one.

However, it is possible to ask whether one can identify a suitable set of ‘rules’ to apply to the GIM2D catalogues to produce a meaningful, final ‘filtered’ catalogue. This catalogue would consist of bulge–disc decompositions where appropriate (using the Sérsic+exponential fits), and single-component Sérsic fits otherwise. The interpretation of the single-component Sérsic fits (as a bulge or a disc) would depend on colour and/or Sérsic index. This same approach could be followed using the de Vaucouleurs catalogue for bulge–disc decomposition but we choose to consider only the more meaningful Sérsic+exponential catalogues here.

For each fit, GIM2D computes the reduced- χ^2 as a measure of the goodness-of-fit for the output model. In most cases, both the Sérsic+exponential fits and the single-component Sérsic catalogues have reasonable reduced- χ^2 values (~ 1), although the Sérsic+exponential reduced- χ^2 values are generally smaller. Although the Sérsic+exponential fits may have a reasonable reduced- χ^2 , this does not indicate whether or not the fit is *appropriate* (i.e. whether the Sérsic function is really corresponding to a bulge and the exponential function to a disc). Therefore, the approach followed here involves analysis of the global properties of each type (including colours, Sérsic indices, and the sizes of components), along with visual examination of examples of each of the eight types.

Objects have a range of B/T values (Fig. 8 shows the B/T distribution for our type 1 galaxies), although we note that the frequency of high- B/T values is small (indeed, only 62/7750 objects are type 8 with $B/T = 1$). This perhaps reflects the fact that the addition of a weak exponential model to a light profile dominated by a Sérsic model can make little difference to the overall total profile (see

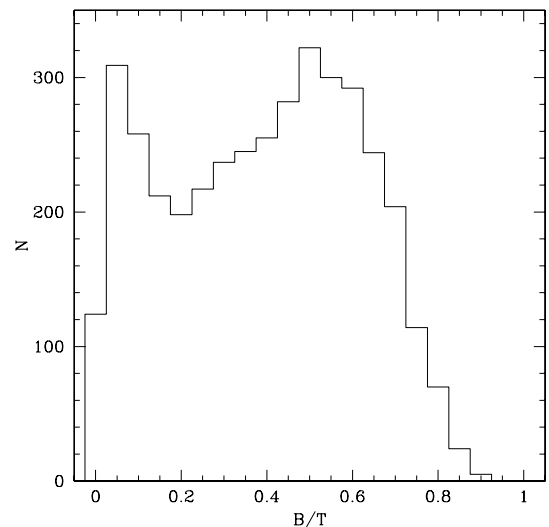


Figure 8. The distribution in B/T for (classic) type 1 galaxies. The lack of objects with very high B/T is notable.

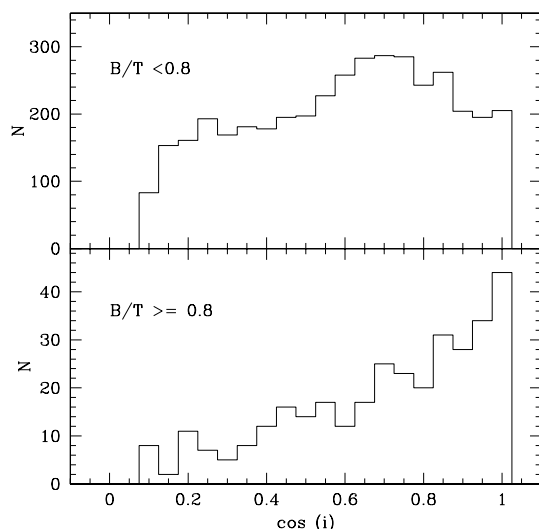


Figure 9. Distribution in $\cos(i)$ for the ‘disc’ component of galaxies with types 1 and 5 with a bulge component having $n > 1.5$. The top panel shows a roughly flat distribution for those galaxies with $B/T < 0.8$, whereas the lower panel, for galaxies with $B/T \geq 0.8$, indicates a suspicious preference for face-on exponential profiles.

e.g. Saglia et al. 1997). The exponential component may represent a weak disc, an isophotal twist, a PSF error, or some perturbation in the profile. This degeneracy means that kinematic measurements are required to test for the presence of a low-luminosity, rotationally supported disc.

Fig. 9 shows the distribution of disc inclinations for spheroid-dominated systems (type 1 and type 5 galaxies with $n > 1.5$) for $B/T < 0.8$ and $B/T \geq 0.8$. For objects with $B/T < 0.8$, the distribution is relatively flat, as expected for a random sample of discs with random orientations in space. However, for $B/T \geq 0.8$, ‘discs’ with inclinations towards face-on dominate, especially for those objects that have been visually classified as E/S0. It is therefore highly improbable these faint discs are all real. Therefore, we choose to replace the Sérsic + exponential fits for type 1 and 5 objects with $B/T \geq 0.8$ with single Sérsic profiles (cf. Trujillo & Aguerrí 2004; Gutiérrez et al. 2004, who replaced objects with $B/T > 0.6$ with single Sérsic profiles).

Driver et al. (2006) have demonstrated the existence of a bimodality in the colour– $\log(n)$ plane for luminous galaxies (when modelled with a single Sérsic function); one can clearly identify a high- n red peak, and a low- n blue peak. The colours referred to here are the $(u-r)_{\text{core}}$ PSF colours from SDSS photometry (see Driver et al. 2006, for more detail of our use of PSF colours). Furthermore, they suggested that the two peaks can be identified with bulges and discs, respectively. This differs in a subtle but important way from the usual interpretation of the colour bimodality, which is credited to early- and late-type galaxies rather than bulge and disc stellar systems. Fig. 10 shows the colour– $\log(n)$ plane for the Sérsic (which one might initially interpret as a ‘bulge’) component for each of the six two-component types we identify (see Fig. 7). The top left-hand panel of Fig. 11 shows the same cumulative raw distribution for all types together. This differs from Driver et al. (2006) in that we have now separated the bulge and disc components, as Driver et al. argued should be done. It is clear from Fig. 10 that most galaxies are ‘classical’ type 1 profiles, and of these, the majority of the ‘bulges’

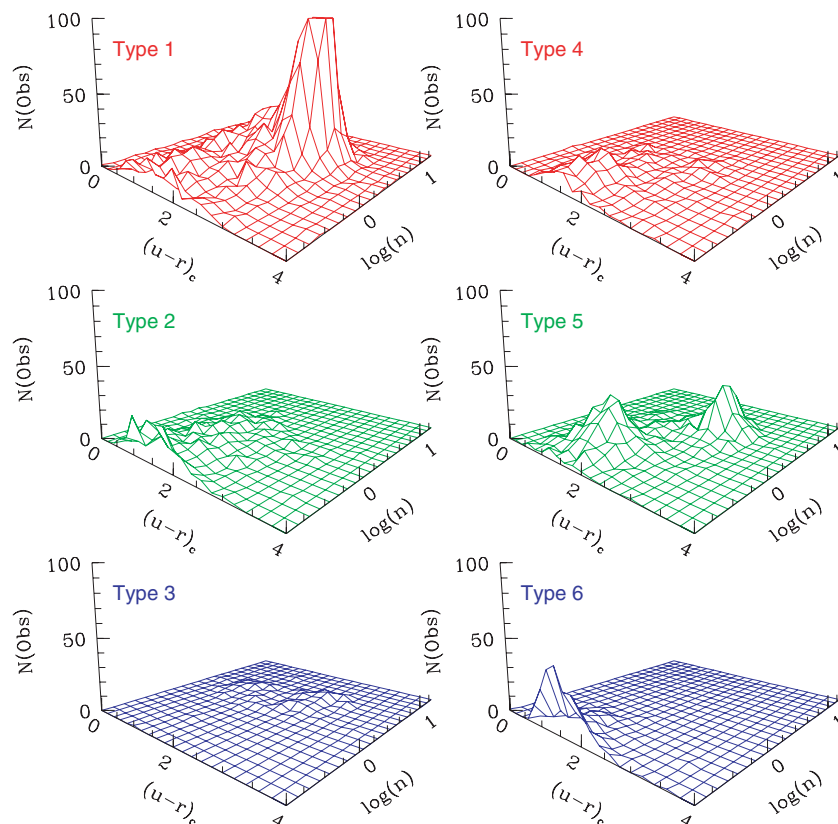


Figure 10. The distribution of galaxy bulges (pre-filtering) in the $(u-r)_{\text{core}}-\log(n)$ plane for each of the six profile types we identify in Section 5.

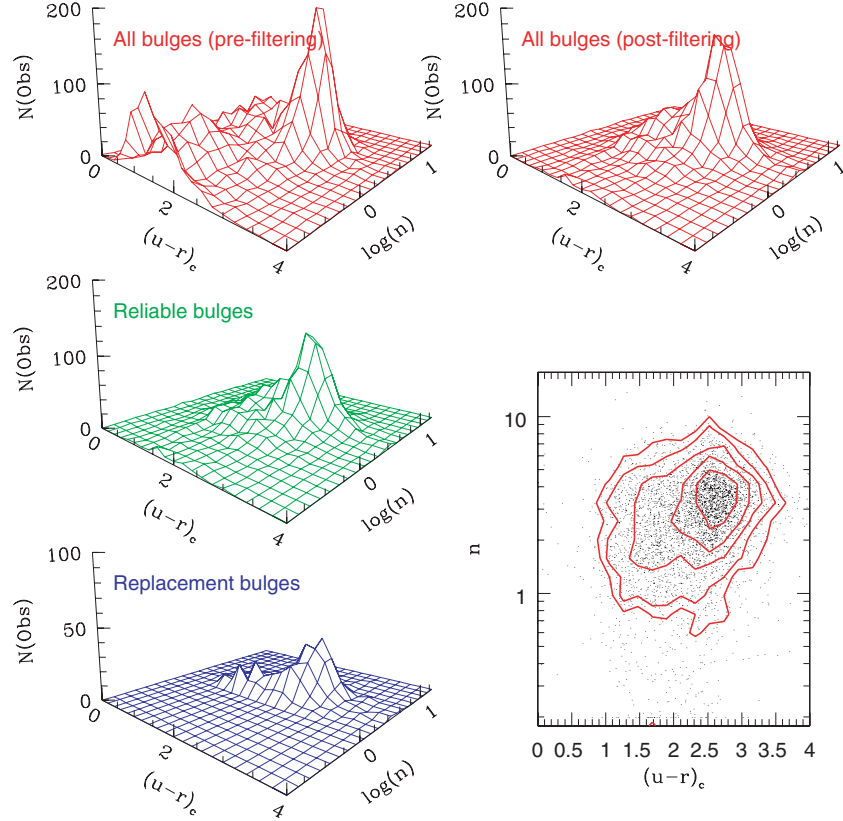


Figure 11. Left-hand column: the distribution of galaxy ‘bulges’ in the $(u-r)_{\text{core}}\text{--}\log(n)$ plane for: (top left-hand panel) raw galaxy bulges (pre-filtering) of all types (see Fig. 10), (middle left-hand panel) bulges from two-component Sérsic + exponential model that pass through the logical filter unchanged, (bottom left-hand panel) replacements from the Sérsic-only catalogue that are interpreted as bulges. The right-hand panels show the distribution of bulges from the final filtered catalogue (reliable Sérsic + exponential bulges, plus replacement Sérsic-only bulges) in 3D (top panel), and in 2D (bottom panel).

are associated with a high- n red peak. However, for most galaxies of types 2–6, and for a small but significant fraction of type 1 galaxies, the bulges do not correspond to the high- n red peak. To investigate this situation further, we now consider each of the profile types in turn.

The majority of the two-component fits correspond to a ‘classic’ *type 1* profile. Analysis of the bulge properties of these galaxies suggests the presence of at least two populations in the majority of cases. The top left-hand panel of Fig. 10 shows that most objects lie in a clear peak around $n \sim 3$, and PSF colour $(u-r)_{\text{core}} \sim 2.5$. These bulges appear to belong to plausible bulge–disc systems, and are accepted by us as correct decompositions, and therefore progress unchanged to the final filtered catalogue. Additionally, there is a tail of objects and a possible second peak around $n \sim 0.5$, with a wider range in colours, albeit generally blue $[(u-r)_{\text{core}} < 2.0]$. This could be indicative of a population of pseudo-bulges or bars. Such a population might be expected in disc-dominated systems ($B/T < 0.5$), and these objects are accepted as having good decompositions and genuine bulges. An additional separation into bulges and pseudo-bulges/bars can be made at a later stage if required. However, pseudo-bulges are unlikely to be found in the high- B/T regime. Fig. 12 shows the distribution in Sérsic index for Sérsic-dominated ($B/T > 0.5$) type 1 galaxies. Based on this distribution, we accept objects with $n > 1.5$ as having a good bulge–disc decomposition and they are included as such in the filtered catalogue, whilst type 1 objects with $n < 1.5$ are replaced with single-component Sérsic fits. These objects appear to be either pure disc systems or dwarf ellipticals.

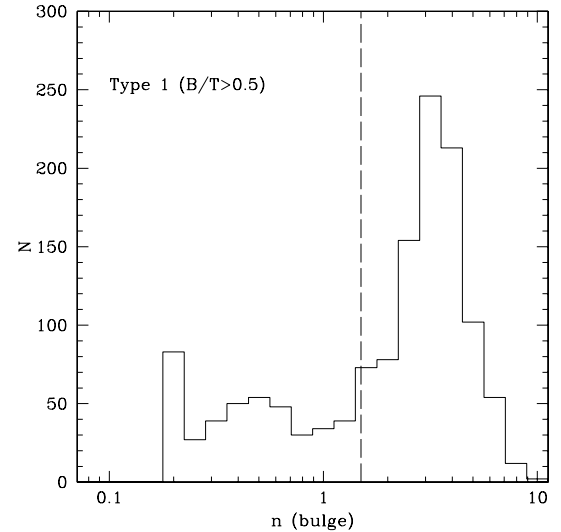


Figure 12. The distribution of bulge Sérsic index, n , for type 1 galaxies that are bulge dominated (i.e. $B/T > 0.5$).

Type 2 galaxies are clearly disc-dominated objects (they all have $B/T < 0.5$), with a possible small bulge. The addition of a weak Sérsic function to an exponential function can be enough to perturb the total profile significantly (see the type 2 example in Fig. 7). However, the modelled perturbation to the total profile is not

always at the centre, and is sometimes at much larger radii (analogous to the type 6 profile shown in Fig. 7, but without the profiles crossing). In these cases, it would be incorrect to interpret the Sérsic function as a bulge, and we therefore impose the additional restriction for type 2 objects that $R_e < 0.5h$, ensuring that only Sérsic functions modelling a central feature are considered as bulge–disc systems. We allow these objects to pass through to the filtered catalogue. Based on the colour–log(n) distribution in Fig. 10, the bulges of the majority of these galaxies do not correspond to the classical red, high- n peak, and may be better interpreted as pseudo-bulges. A small fraction of these objects are red, but they are all highly inclined systems, and thus likely red due to dust. Those objects with $R_e > 0.5h$ (i.e. the Sérsic function does not correspond to a central perturbation) are replaced with single-component Sérsic fits, and are interpreted as disc-only systems.

Only a small fraction of galaxies are classified as *type 3*. These fits are erroneous and are sometimes caused by nearby neighbours (which GIM2D would be unaware of) contributing extra flux at large radii. They are generally red, bulge-dominated systems, with high n and we choose to replace them with a Sérsic-only fit, which will typically be later interpreted as a bulge-only system. This class does contain a fraction (<1 per cent) of genuine bulge–disc systems that will be missed.

Many *type 4* profiles can be considered true inversions, with the exponential function fitting a central feature, and the Sérsic function fitting the outer disc. This can occur for a number of reasons. A PSF error can mean that the exponential is used to fit a sharp ‘spike’ at the centre of the profile. Such spikes are always much smaller than the HWHM of the PSF. In other cases, the galaxy appears to be an irregular disc with active star formation. The size and shape of the two components can be comparable, especially for the redder galaxies, when the modelled galaxy is often a dwarf. In all cases, the bulge–disc interpretation would be erroneous and a single Sérsic fit is preferred in the filtered catalogue. However, a fraction of these galaxies appear to be genuine bulge–disc systems with severe disc truncation. This seems to be a real phenomenon, and is likely to be an increasing problem with future, deeper data sets. Similarly, at higher redshifts, discs are seen to be described with a Sérsic function requiring $n < 1$ (Tamm & Tenjes 2006). Unfortunately, modelling disc truncation is beyond the scope of GIM2D, and it is not possible to fit the 2D images accurately. Therefore, we choose to replace these fits with single-component Sérsic functions, and accept that a small fraction (<5 per cent) of bulge–disc systems may be missed, or rather, not decomposed.

The *type 5* galaxies all have $B/T > 0.6$, and are therefore dominated by the Sérsic component. The addition of an exponential function (that does not cross) makes little difference to the total profile. The distribution in Sérsic index and colour is clearly bimodal (Fig. 10), and there is a correlation between (two-component) Sérsic–‘bulge’ parameters, and the Sérsic-only parameters. These galaxies tend to be blue, low- n disc-only systems, or red, high- n bulge-only systems (i.e. spheroids). They are best fitted by a single Sérsic component, and these fits are therefore used in the filtered catalogue.

The fits to *type 6* galaxies are clearly incorrect if interpreted as bulge–disc decompositions. From Fig. 10, the ‘bulge’ components have very low n , and blue ($u - r$) colours. These galaxies also have low Sérsic index ($n < 1$) from the Sérsic-only fits. They appear to be either dwarf galaxies or very flat ($n < 1$) discs with active star formation and/or other irregularities. In all cases, a single Sérsic fit is adopted as more appropriate.

Finally, those objects that only have one component from the Sérsic + exponential model fits (*type 7* and *type 8*) are replaced with single-component Sérsic-only fits.

In summary, all profiles were replaced with Sérsic-only fits except for types 1 and 2, which generally keep the two-component bulge–disc decomposition. The exceptions are when (i) $B/T > 0.8$, or (ii) a low- n (<1.5) Sérsic component dominates ($B/T > 0.5$) for the type 1 galaxies, and (iii) when $R_e > 0.5 \times h$ (i.e. the Sérsic function models a non-central perturbation) for the type 2 galaxies. The logical filter is summarized in Fig. 13. After the filtering process, the full catalogue contains 3454 two-component objects where the Sérsic component is treated as a bulge, and the exponential component is treated as a disc. The remaining galaxies in the catalogue (4296 objects) are fitted with a single Sérsic component. The distribution of these Sérsic-only objects in the colour– n plane is shown in Fig. 14, where the bimodal nature is evident. Based on this distribution, we choose $n = 1.5$ as the division between the two populations. We classify 825 galaxies with $n \geq 1.5$ as bulge-only objects, and 3471 galaxies with $n < 1.5$ as discs. As already discussed, these replacements will include a small fraction (<6 per cent) of type 3 or type 4 galaxies that are genuine bulge–disc systems, that are misinterpreted here as bulge-only or disc-only.

As a useful verification of this bulge- or disc-only interpretation, we also looked at the above Sérsic-only replacements in the $R^{1/4} +$ exponential catalogue. For the replacement ‘disc-only’ objects, 80.1 per cent of galaxies had a best-fitting $R^{1/4} +$ exponential model with $B/T = 0$ (i.e. GIM2D found a single exponential disc the most optimal model). The remainder of the replacement discs were all in disc-dominated systems with $B/T < 0.5$ (half of them with $B/T < 0.1$). For the replacement ‘bulge-only’ objects, the $R^{1/4} +$ exponential model produced mostly high- B/T output, with a median of $B/T \sim 0.8$, suggesting that this population is indeed dominated by E/S0 galaxies.

6 REPEAT OBSERVATIONS AND PARAMETER ACCURACY

The geometry of the MGC is such that each pointing of the Isaac Newton Telescope (INT) Wide Field Camera overlaps by approximately 0.027 deg^2 with the previous one (see fig. 2 in Liske et al. 2003), building up a mosaiced strip across the sky. Objects that lie in these overlap regions are therefore observed twice. Although the MGC catalogues only utilize one of these observations, the imaging data exist and SEXTRACTOR catalogues, and GIM2D input images were prepared for all 702 duplicate galaxies. Here, we remove those objects with incorrect masks (see Section 4.2), reducing the number of twice-observed comparison objects to 682.

In each case, repeat observations lie on a different CCD of the WFC, with different PSFs, airmasses, sky brightnesses, noise, and seeing conditions. Often, the observations were carried out on a different night or even as part of different observing runs several months or years apart. They therefore provide an excellent test of the repeatability of GIM2D fits for a diverse and representative sample of galaxies under different conditions.

In all three catalogues acceptable repeatability (most measurements agree better than 20 per cent) is obtained if a bulge/disc component size limit is imposed such that the half-light radius is larger than the HWHM of the seeing disc (half-light radius $> 0.5 \times$ seeing). Bulges are compared when $R_e > 0.5\Gamma$, and discs are compared when $1.678h > 0.5\Gamma$, where Γ is the average seeing for the image the galaxy lies in. Below this threshold, the differences between repeat measurements begin to increase. In addition, we also find

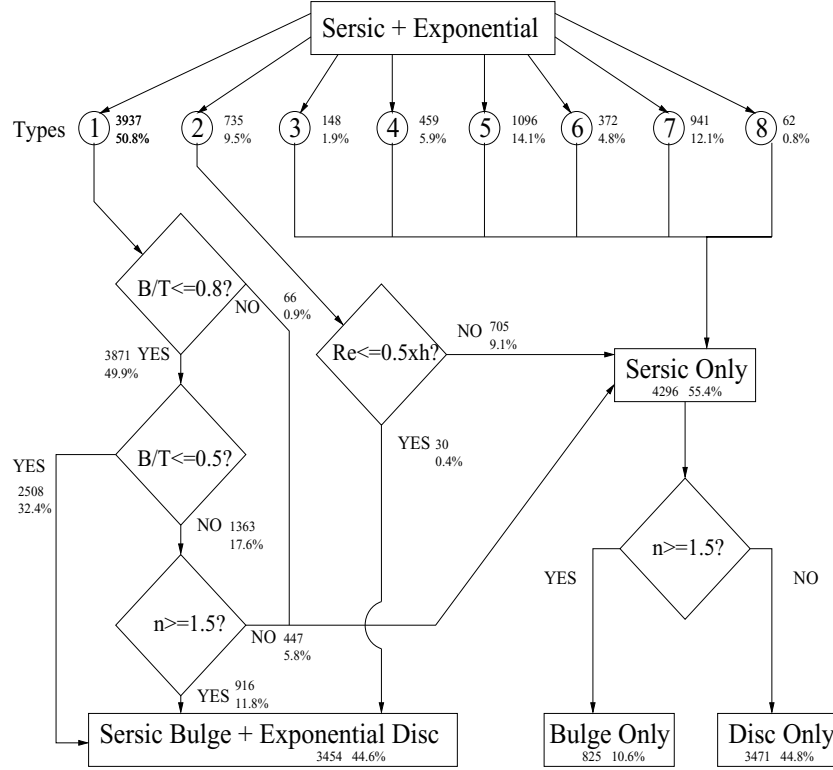


Figure 13. A summary of the steps involved in the logical filter for the Sérsic + exponential catalogue.

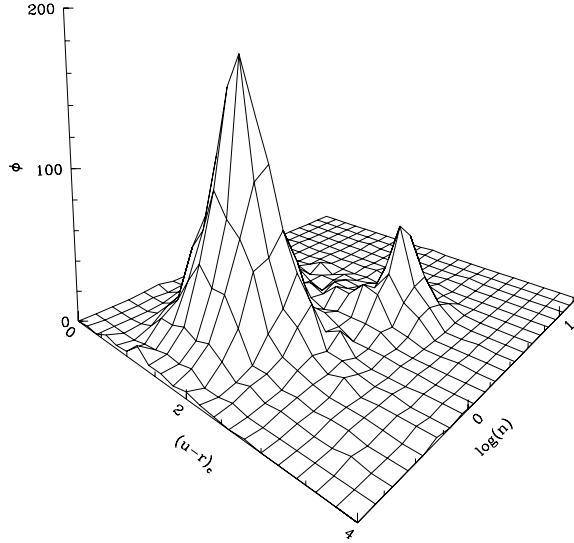


Figure 14. The distribution of those galaxies replaced with Sérsic-only fits by the logical filter in the $(u - r)_{\text{core}} - \log(n)$ plane. We choose $n = 1.5$ as the division between the two populations.

that the repeatability is poor for less-luminous components, and we therefore impose a $M = -17$ B mag limit on the component magnitudes. Note that the uncertainties discussed here are not included in the final structural catalogues which only contain the 68 per cent confidence intervals computed by GIM2D (see Section 3.4).

Profiles from the repeat observations have been interpreted according to the rules described in Section 5.1, and replacements made where necessary. In most cases, the profile type is the same for each pair of observations of an object, but where the profile types differ,

components interpreted as bulges or discs are directly compared (e.g. even if a galaxy has a type 2 profile in one measurement and a type 1 profile in the other, the bulge and disc components are still compared). When one measurement of an object has resulted in a single-component Sérsic profile and the other measurement uses a two-component profile (e.g. type 1), the Sérsic-only profile is interpreted as either a bulge or a disc (see Section 5.1), and compared with the corresponding component in the other fit. Type discrepancies such as this occur about 12 per cent of the time. For each parameter, we compute the mean residual and the 3σ clipped standard deviation. In all cases, the size of residuals correlates with the apparent half-light radii of the components.

Fig. 15 shows a comparison between bulge and disc parameters from repeat observations for the filtered catalogue using two-component Sérsic + exponential fits (or Sérsic replacements). In all cases, the mean is close to zero. We find bulge R_e differences have a standard deviation of 12.2 per cent, the Sérsic index, n , has a standard deviation of $\Delta \log(n) = 13.2$ per cent. Ellipticity differences have a standard deviation of 4.1 per cent, and the bulge magnitudes, M_{bulge} , have a standard deviation of 0.10 B mag. For discs, a larger sample can be used, as more discs are larger than the $0.5I'$ cut. Scalelengths, h , have a standard deviation of 6.6 per cent, and disc inclinations, $\cos(i)$, have a standard deviation of 4.7 per cent. Finally, disc magnitudes have a standard deviation of 0.15 B mag. The largest residuals are mostly due to those objects that have different types between repeat observations (e.g. one observation results in a high- B/T type 1 bulge–disc classification, and the other observation results in a type 5 bulge-only classification in which cases only the bulge parameters are compared).

Fig. 16 shows histograms of the distribution in differences between parameters from repeat observations using the de Vaucouleurs + exponential catalogue. Once again, the catalogues have been

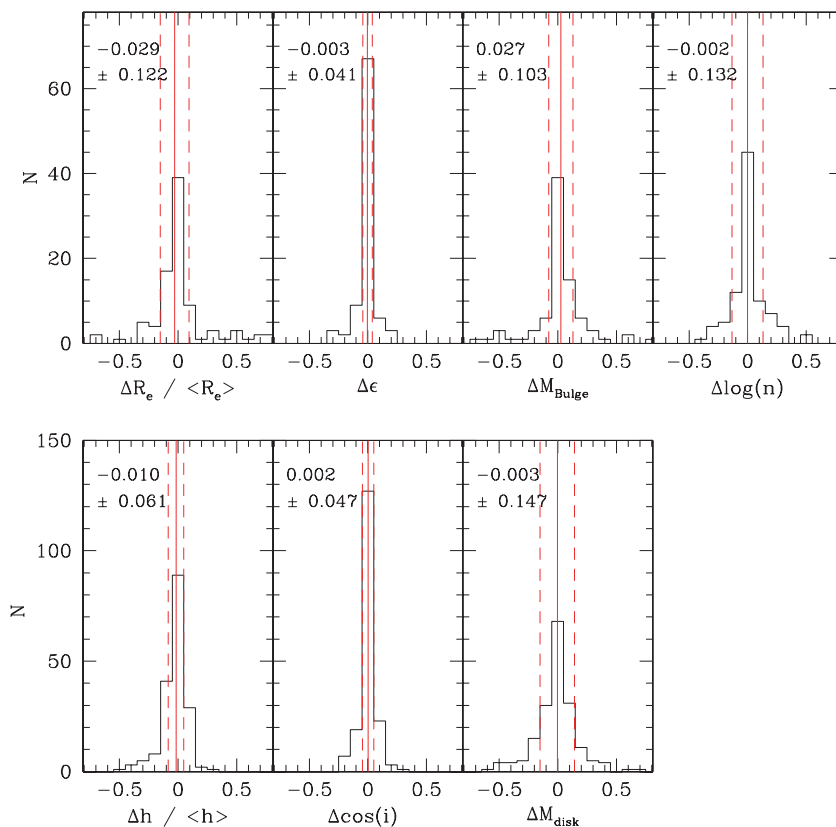


Figure 15. Parameter comparison between repeat observations of galaxies. Bulge (top panel) and disc (lower panel) parameters are derived from Sérsic–bulge/exponential-disc filtered catalogues. The solid lines correspond to the mean difference between repeat measurements and the dashed lines show the standard deviation. In each panel, the mean and standard deviations are noted.

filtered according to the rules described in Section 5. These measurements also show an acceptable level of repeatability, although the scatter in the bulge differences is larger than that found using the Sérsic + exponential catalogue. Bulge standard deviations are: $\Delta R_e / R_e = 32.7$ per cent, $\Delta \epsilon / \epsilon = 9.5$ per cent, and $\Delta M_{\text{bulge}} = 0.29$ mag. For discs, measurements are comparable to the Sérsic + exponential catalogue, with standard deviations of $\Delta h / h = 6.7$ per cent, $\Delta \cos(i) = 4.9$ per cent and $\Delta M_{\text{disc}} = 0.11$ mag.

Residuals for measured parameters for single-component Sérsic fits are shown in Fig. 17. As would be expected this much simpler model produces much more repeatable results. In this case, the standard deviations are $\Delta R_e / R_e = 3.7$ per cent, $\Delta \epsilon / \epsilon = 2.0$ per cent, $\Delta M = 0.04$ mag, and $\Delta \log(n) = 4.2$ per cent.

7 FUNDAMENTAL BULGE AND DISC PROPERTIES

To demonstrate the consistency and suitability of the separation into bulge and disc populations, we recover two fundamental statistical results: the Kormendy relation (Kormendy 1977) and the relation between disc central surface brightness and disc scalelength (de Jong 1996b; Graham 2001). In Fig. 18, the size–surface brightness relation is shown for *all* bulges with $R_e > 0.5\Gamma$ and $M_{\text{bulge}} < -17$ mag, along with the relation of Kormendy (1977). The majority of red bulges follow the Kormendy relation well (especially for large values of B/T); however, the smaller population of blue bulges do not. For reasons explained in Graham & Guzmán (2003), faint spheroids do not follow the Kormendy relation, having smaller R_e , and fainter $\langle \mu_e \rangle$.

Fig. 19 shows the distribution in scalelength, h , and central surface brightness, μ_0 , for discs from the Sérsic+exponential catalogue after filtering (see Section 5.1). Only galaxies with $1.678h > 0.5\Gamma$, and $M_{\text{disc}} < -17$ mag (see Section 6) are shown. The dashed line shows the $M_{\text{disc}} = -17$ B mag limit. It is clear that larger discs have larger (i.e. fainter) values for their central surface brightness as shown by other authors (de Jong 1996b; Graham 2001).

The right-hand panel of Fig. 11 shows the distribution of bulges in the colour– $\log(n)$ plane from the Sérsic+exponential catalogue (post-filtering). This distribution can be compared with that presented in Driver et al. (2006) who considered *total* rather than *component* properties, and identified two distinct peaks. In Fig. 11, the bulges clearly form a single red, high- n peak, although there is a small shoulder of bluer, low- n objects. That the majority of bulges identify with the red, high- n peak supports the conclusions of Driver et al. (2006) that the colour bimodality reported in the galaxy population is best explained by two fundamental components: bulges and discs, rather than two different galaxy populations. Furthermore, this probably reflects two dominant formation processes and epochs. The small number of blue, low- n bulges may also be evidence of a third population of pseudo-bulges resulting from secular evolution. The bimodal nature of the different components is again evident in Fig. 20, which shows the relationship between the model μ_0 , and M_B for bulge, disc, and pseudo-bulge components. It is clear that there are two distinct groupings with the high surface brightness bulges and the low surface brightness discs. The small number of blue, pseudo-bulges appear to have intermediate surface brightnesses.

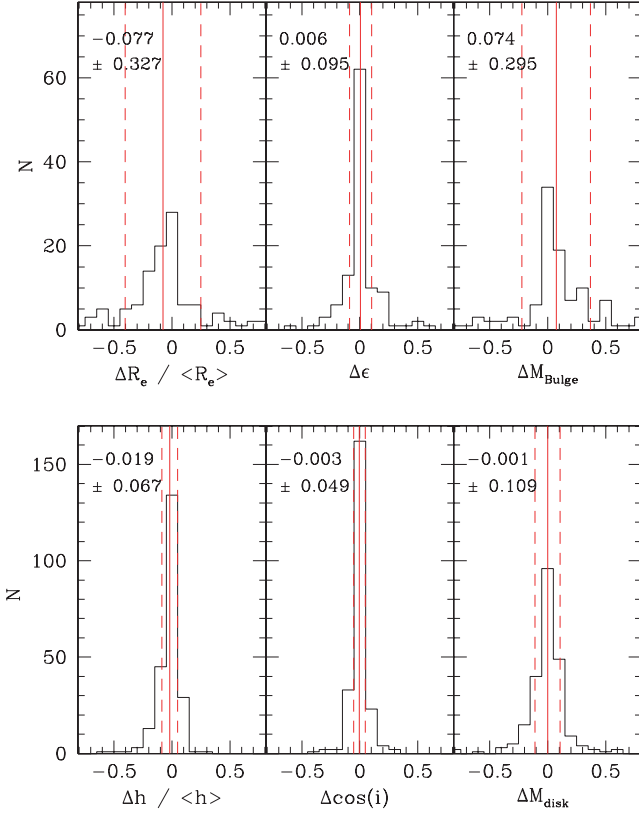


Figure 16. Comparison between repeat observations of galaxies for bulge (top panel) and disc (lower panel) parameters derived from $R^{1/4}$ bulge + exponential disc filtered catalogues. The solid lines correspond to the mean difference between repeat measurements and the dashed lines show the standard deviation. In each panel, the mean and standard deviations are noted.

8 CONCLUSIONS

We have used GIM2D to perform 2D model fits (including bulge–disc decomposition) for 10 095 galaxies with $B_{\text{MGC}} < 20$ mag from the MGC. We initially produced three catalogues using: (1) a single-component Sérsic model, (2) a Sérsic+exponential bulge–disc model, and (3) an $R^{1/4}$ +exponential bulge–disc model. We find that there is good agreement between GIM2D centroids, magnitudes, and half-light radii, with those in the Liske et al. (2003) MGC catalogues. However, there are a significant number of objects that have

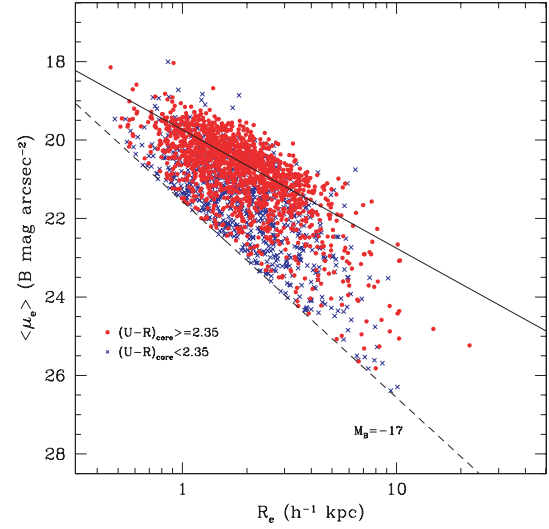


Figure 18. The $\langle \mu_e \rangle$ – $\log(R_e)$ distribution for all MGC bulges. The red circles show objects with $(u-r)_{\text{core}} \geq 2.35$, and the blue crosses denote objects with $(u-r)_{\text{core}} < 2.35$. The dashed line shows the $M_{\text{bulge}} = -17$ B mag limit, and the solid line shows the Kormendy (1977) relation. The red population follows the Kormendy relation well, with most of the scatter coming from objects with $B/T < 0.5$. The blue (pseudo-)bulges do not appear to fit the relation.

incorrect mask images from SEXTRACTOR which had to be corrected manually.

When a two-component model is used, we find that a significant fraction of galaxies have mathematically ‘good’ fits, which may not be the most appropriate or meaningful. The components may be inverted, cross each other once, twice, or not at all. In addition, it is also important to stress that many galaxies are *not* two-component systems, and simply interpreting one component as ‘bulge’ and the other as ‘disc’ would clearly be wrong. We identify eight distinct profile types based on which of the two components dominate at the galaxy centre, at $\mu = 26$ mag arcsec $^{-2}$, and whether the components cross.

The majority (~50 per cent) of objects are ‘classical’ type 1 galaxies where the Sérsic function dominates at the centre (modelling a bulge), and the exponential function dominates the outer regions (modelling a disc). The remaining objects often require more careful interpretation. The different types are sometimes due to

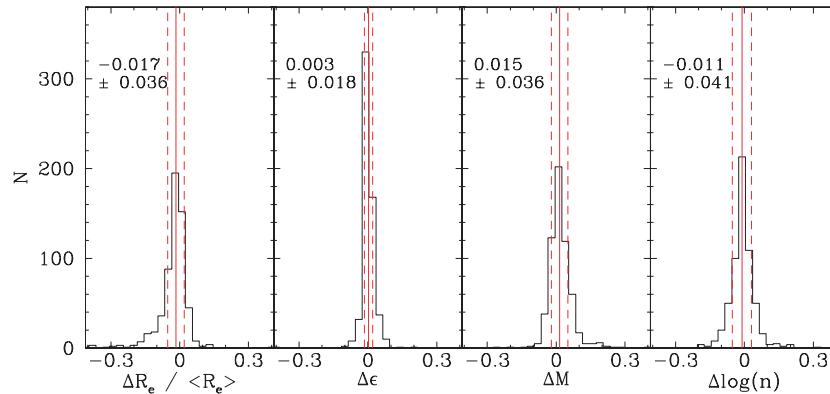


Figure 17. Comparison between repeat observations of galaxies for parameters derived from single-component Sérsic fits. The solid lines correspond to the mean difference between repeat measurements and the dashed lines show the standard deviation. In each panel, the mean and standard deviations are noted.

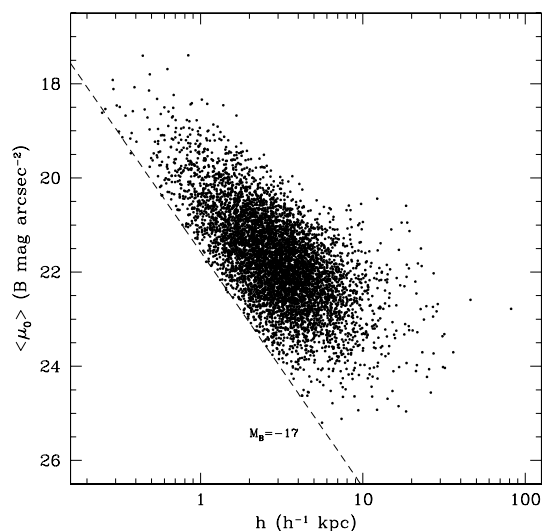


Figure 19. The μ_0 – $\log(h)$ distribution for all reliable discs in the MGC (using the filtered Sérsic+exponential catalogue). The dashed line shows the $M_B = -17$ limit. Discs with larger scalelengths have fainter central surface brightnesses.

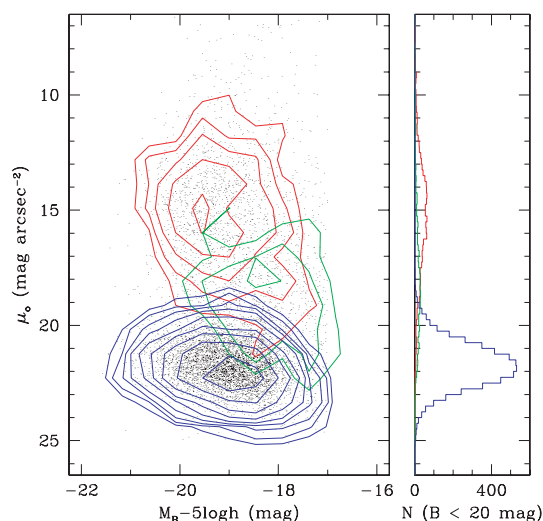


Figure 20. The distribution of galaxy component properties in the M_B – μ_0 plane is shown by the dots. Red contours outline the distribution of bulge components, and blue contours outline the distribution of disc components. Two clear populations are evident. The magenta contours outline the blue $[(u - r)_{\text{core}} < 2.35]$ bulge components, which appear to lie in an intermediate position. The right-hand panel shows histograms of the number of each type of component. The number of discs is boosted because they are more likely to meet the size criteria than bulges (or pseudo-bulges).

phenomena such as disc truncation, multiple nuclei, or strong irregularities, all of which lie beyond the scope of the simple GIM2D model. Using the ‘type’ scheme, we implement a strategy to ensure only genuine bulge–disc systems are fitted with a Sérsic+exponential model, and replace all other objects with single-component Sérsic fits. In most cases, only single-component systems end up with Sérsic-only fits. A small number (<6 per cent) of genuine bulge+disc systems are classified as type 3 or type 4 (especially those with disc truncation), and will therefore be misclassified as single-component systems. This ‘logical filtering’ process results in a fourth catalogue, where each galaxy is treated as either bulge+disc,

bulge-only, or disc-only, and it is this catalogue that we suggest contains the most appropriate, physically meaningful modelling of the galaxy population. All five structural catalogues are publicly available at the MGC website (<http://www.eso.org/~jliske/mgc>).

To test the repeatability and accuracy of our measurements, we applied GIM2D twice to the objects that lie in the overlap regions between the individual pointings that make up the MGC strip. We find that if size and absolute magnitude cuts are imposed, parameter measurements are repeatable at less than the 15 per cent level. Although the catalogues contain entries for all objects, we recommend imposing cuts in size (half-light radius $> 0.5\Gamma$) and component absolute magnitude ($M < -17 B$ mag) in order to obtain reliable measurements. To demonstrate the accuracy of the final, logically filtered catalogue, we recover the fundamental Kormendy and μ_0 – $\log(h)$ relations for bulges and discs, respectively. In a series of future papers, the catalogues presented here will be used in detail to measure bulge and disc luminosity functions, bivariate brightness distributions, and size distributions. We are also using the catalogues to measure the supermassive black hole mass function and to study the effects of disc opacity.

Finally, we have used the catalogues to show that the galaxy colour– $\log(n)$ bimodality is due to the two-component nature of galaxies, rather than two distinct galaxy populations. Luminous bulges generally occupy the red, high- n peak, and discs occupy the blue, low- n peak. There is also some evidence for a third population of blue, pseudo-bulges. The observed bimodality may be the end-result of two distinct processes and time-scales associated with bulge and disc formation. We conclude that routine bulge–disc decomposition is essential at all redshifts to fully understand the evolution of the luminous ($M_B < -17$ mag) galaxy population. Three major steps forward are now required: (1) high-resolution, deep near-infrared survey data, (2) the expansion of bulge–disc decomposition software to accommodate real phenomena such as nuclei and disc truncation, and (3) deeper studies to characterize the dwarf ($M_B > -17$ mag) population.

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