Galaxy And Mass Assembly (GAMA): the wavelength-dependent sizes and profiles of galaxies revealed by MegaMorph


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Accepted 2014 March 31. Received 2014 February 27; in original form 2013 November 26

ABSTRACT

We investigate the relationship between colour and structure within galaxies using a large, volume-limited sample of bright, low-redshift galaxies with optical–near-infrared imaging from the GAMA survey. We fit single-component, wavelength-dependent, elliptical Sérsic models to all passbands simultaneously, using software developed by the MegaMorph project. Dividing our sample by $n$ and colour, the recovered wavelength variations in effective radius ($R_e$) and Sérsic index ($n$) reveal the internal structure, and hence formation history, of different types of galaxies. All these trends depend on $n$; some have an additional dependence on galaxy colour. Late-type galaxies ($n_r < 2.5$) show a dramatic increase in Sérsic index with wavelength. This might be a result of their two-component (bulge-disk) nature, though stellar population gradients within each component and dust attenuation are likely to play a role. All galaxies show a substantial decrease in $R_e$ with wavelength. This is strongest for early-types ($n_r > 2.5$), even though they maintain constant $n$ with wavelength, revealing that ellipticals are a superimposition of different stellar populations associated with multiple collapse and merging events. Processes leading to structures with larger $R_e$ must be associated with lower metallicity or younger stellar populations. This appears to rule out the formation of young cores through dissipative gas accretion as an important mechanism in the recent lives of luminous elliptical galaxies.

Key words: galaxies: general – galaxies: structure – galaxies: fundamental parameters – galaxies: formation

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1 INTRODUCTION

It is common to describe galaxies by a few key properties, such as luminosity, colour, size and ellipticity, which are (at least in the local universe and at optical and near-infrared wavelengths) indicative of the total mass, average age, and spatial extent of their stellar contents. At a slightly more detailed level, one may characterise a galaxy in terms of its internal structure, or morphology: the presence and relative strength of features such as disks, bulges, bars, rings and spiral arms. Each of these features represents a distinctive distribution of stars, in terms of both their positions and velocities. Unfortunately, resolved stellar velocities are difficult to obtain, particularly for large samples of distant galaxies. The largest studies of the internal structure of galaxies must therefore inevitably rely on imaging data.

Galaxies principally come in two morphological types: ellipticals and disk galaxies. Ellipticals have a simple, smooth appearance, show old stellar populations and live preferably in denser environments (see, e.g., Dressler et al. 1997; Kauffmann et al. 2003; Brinchmann et al. 2004). Spirals primarily comprise a thin disk, containing a spiral arm pattern; possess younger stellar populations, and avoid dense regions (e.g., Freeman 1970; Blanton & Moustakas 2009 and references therein). However, spirals often also contain a spheroidal ‘bulge’, a structure similar in colour and shape to a small elliptical galaxy, at their centre (Andredakis, Peletier, & Balcells 1995); though bulges appear to be denser than present day elliptical galaxies, (e.g., Graham & Worley 2008; Graham 2013). The relative size and importance of the bulge and the appearance of the spiral features vary substantially, resulting in a range of spiral morphologies (de Jong 1996a). Lenticular galaxies sit at the intersection of ellipticals and spirals. They display similarities to both, often being dominated by a bulge, but also by definition, containing a spiral-free, disk-like component. Ellipticals and lenticulars can be hard to distinguish from their appearance. Indeed, over the past decade many galaxies that were thought to be ellipticals have been discovered to contain rotating disks, and thus are actually lenticular galaxies.

From the latest models of galaxy formation and evolution, it is becoming clear that there is a more fundamental distinction in the galaxy population than that between elliptical, lenticular, and spiral galaxies (e.g., Ellis, Abraham, & Dickinson 2001). To truly understand galaxy evolution, one must separate the components of galaxies: spheroids and disks. Elliptical galaxies are dominated by a single spheroidal component, while most spiral and lenticular galaxies contain both a spheroid (the bulge) and a disk. The striking difference between galaxy types may primarily be a result of variation in the relative prominence of the spheroid and disk components.

A common way of describing the structure of galaxies is through the Sersic index $n$, which describes the radial concentration of the projected light distribution. The Sersic (1968) function is given by:

$$I(r) = I_e \exp \left(-b_n \left(\frac{r}{R_e}\right)^{\frac{1}{n}} - 1\right)$$

where $R_e$ is the effective radius (that is, the radius containing half of the model light), $I_e$ is the intensity at the effective radius, $n$ is the Sersic index, and $b_n$ is a function of Sersic index and is such that $\Gamma(2n) = 2\pi(2n, b_n)$, where $\Gamma$ and $\gamma$ represent the complete and incomplete gamma functions, respectively (Ciotti 1991). Andreazza, Melchior, & Jahnke (2011) showed that this is the simplest function one could consider to model a galaxy profile, being the first-order Taylor expansion of any real light profile. When $n$ is equal to the values 0.5, 1 and 4 (and $b_n$ assumes the values of 0.676, 1.676 and 7.676, respectively), the Sersic profile is equivalent to a Gaussian, exponential and de Vaucouleurs profile, respectively. A Sersic projected profile implies a 3D luminosity density profile involving the Fox $H$ function (Bues & van Hese 2011).

Elliptical galaxies are typically regarded as single-component structures, hence $n$ is a reasonably fundamental description of the profile (but see Cappellari et al. 2011 and Huang et al. 2013a). However, when fitting a single-Sersic profile to a disk galaxy the resulting $n$ reflects the contribution of both the disk and the bulge to the light distribution.

We note that some degeneracy exists, in that appropriate small variations in $R_e$ and $n$ can produce similar surface brightness profiles, which are indistinguishable at the resolution and depth of the data we consider. The two quantities are also found to be correlated in the galaxy population. However, e.g., Trujillo, Graham, & Caon (2001) showed that the correlation between $n$ and $R_e$ is definitely not explained by parameter coupling in the fitting process; this trend between galaxy structure and size exists also when one uses model-independent values. Indeed, it is a natural consequence from the relations existing between the model-independent parameters: total luminosity, effective radius and effective surface brightness.

All galaxies show variations in colour to some degree. These often appear as radial colour gradients, with the centres of galaxies generally redder than their outer regions (at least in the more luminous galaxy population; Jansen et al. 2000). Even the colour of elliptical galaxies varies significantly with radius (e.g., La Barbera et al. 2010b).

Colour gradients provide important information for understanding how galaxies form and evolve. For example, steep gradients are expected when stars form during strongly-dissipative (monolithic) collapse in galaxy cores. In such a scenario, gas is retained by the deep potential well, with consequently extended star formation activity and greater chemical enrichment of the inner regions (e.g., Kobayashi 2004).

In early-type galaxies the main driver of colour gradients is probably metallicity (see, e.g., Saglia et al. 2000; Tamura & Ohta 2000; La Barbera et al. 2003; Spolaor et al. 2009; Rawle, Smith, & Lucey 2010; den Brok et al. 2011 and references therein), even though the contribution of the age (see, e.g., La Barbera et al. 2002; La Barbera & de Carvalho 2009; La Barbera et al. 2012) and even dust (see, e.g., Guo et al. 2013; Pastrav et al. 2013a) cannot be ignored. Structurally, ellipticals may appear to be single-component systems, but that component certainly does not possess a homogeneous stellar population.

Colour gradients are typically stronger in bulge-disk systems. Bulges tend to contain older, redder stars of higher metallicity than those found in the disks of galaxies (e.g., Johnston et al. 2012 and references therein). Shorter optical wavelengths are more sensitive to the young, blue populations typically found in disks, whereas longer (optical and near-infrared) wavelengths increasingly trace the old stellar population of both components. Most late-type galaxies therefore display a substantial colour gradient from red centres to blue outskirts, (de Jong 1996b; Gadotti & Dos Anjos 2001; MacArthur et al. 2004), though peculiar galaxies can show opposing trends (Taylor et al. 2005).

In addition to stellar population gradients, the dust content of a galaxy can produce colour gradients and influence the measured structural parameters in a wavelength dependent manner (Peletier & Balcells 1996; Möllenhoff, Popescu, & Tuffs 2006; Graham & Worley 2008; Kelvin et al. 2012; Pastrav et al. 2013a; Rodriguez et al. 2014; RAS, MNRAS 000, 1–24).
It remains unclear whether dust attenuation or stellar population gradients are the dominant factor in determining how observed galaxy structure varies with wavelength. However, it may also depart from a Sérsic profile, which means the parameters are optimal.

This approach maximizes the signal-to-noise available to vary. However, it is not clear how to fairly determine such fiducial values. When fitting images at different wavelengths completely independently, statistical and systematic variations in the recovered centre, ellipticity, position angle, etc. will translate into noise in the recovered trends for $n$ and $R_e$. In general, therefore, the values measured for $n$ and $R_e$ will depend on the observed wavelength.

Some works have started investigating the wavelength dependence of galaxy structure, fitting Sérsic models independently to images in different wavebands. La Barbera et al. (2010) presented the first time a careful analysis of the structural parameters of low-redshift early-type galaxies as a function of wavelength. They showed that $R_e$ decreases by 35% from the optical to the near-infrared (NIR), reflecting the internal colour gradients in these systems. Their Sérsic indices span a domain from ~2–10, with a median of 6 for all wavebands. Kelvin et al. (2012) presented similar two-dimensional, single-Sérsic model fits to a large sample of low-redshift galaxies. They found that the mean Sérsic index of early-types shows a smooth variation with wavelength, increasing by 30% from $g$ through $K$, while the effective radius decreases by 38% across the same range. In contrast, late-types exhibit a more extreme change in Sérsic index, increasing by 52%, but a more gentle variation in effective radius, decreasing by 25%. These trends are interpreted as due to the effects of dust attenuation and stellar population/metallicity gradients within galaxy populations.

When fitting images at different wavelengths completely independently, statistical and systematic variations in the recovered centre, ellipticity, position angle, etc. will translate into noise in the recovered trends for $n$ and $R_e$. This is particularly an issue if one wants estimates of the wavelength dependence of structure on a galaxy-by-galaxy basis. To address this, some parameters may be fixed to fiducial values, while the parameters of interest are allowed to vary. However, it is not clear how to fairly determine such fiducial values.

In this paper we build upon the work of La Barbera et al. (2010) and Kelvin et al. (2012), by fitting a single, wavelength-dependent model to all the data simultaneously. This is made possible using an extended version of GALFIT (Peng et al. 2002, 2010) developed by the MegaMorph project (Bamford et al. 2012; Haußler et al. 2013) hereafter H13, Vika et al. (2013) and Bamford et al. in prep.). This approach maximizes the signal-to-noise available to constrain the model and ensures that the parameters are optimal for the whole dataset. The most advantages of this approach are expected when decomposing galaxies with multiple components (e.g., Cameron et al. 2009). Making colour information available to the fit increases the robustness with which the components can be separated, and hence improves the accuracy and physical meaningfulness of their recovered parameters. However, to begin we have explored the performance of our technique in fitting single-component models. H13 have tested the new method on large datasets, automating both the preparation of the data and the fitting process itself by extending the existing GALFIT (Barden et al. 2012) code. Vika et al. (2013), on the other hand, studied nearby galaxies and assessed our method by fitting artificially-redshifted versions of these galaxies.

Having at our disposal structural parameters obtained via a consistent multi-wavelength approach from MegaMorph, we can now study the wavelength dependence of Sérsic index and effective radius for both individual galaxies and sample populations. In this paper we quantify these trends using the ratio of $n$ and $R_e$ at two wavelengths. These ratios provide a simple but powerful parametric way of considering galaxy colour gradients, which reveal information about the prevalence of galaxies with different internal structures, and how this varies with other galaxy properties. At a more practical level, quantifying how $n$ and $R_e$ vary with wavelength is crucial for removing biases when comparing measurements made using different bandpasses or at different redshifts.

The paper is organised as follows: in §2 we present the dataset used for the analysis and describe the properties of the sample we analysed. In §3, we show our results for the wavelength dependence of Sérsic indices and effective radii, first by considering trends for subsamples of the galaxy population and then by quantifying the behaviour of individual galaxies. In §4 we discuss the interpretation of our measurements and demonstrate how they relate to the visual appearance of galaxies. In §5 we discuss our results in the context of previous work. Finally, in §6 we summarise and present our conclusions.

The analysis has been carried out using a cosmology with $(\Omega_m, \Omega_{\Lambda}, h) = (0.3, 0.7, 0.7)$ and AB magnitudes.

## DATA

### 2.1 Sérsic models and parent sample selection

The sample of galaxies considered in this paper has been previously presented in H13. A detailed description of the selection criteria, robustness of the fits and properties of our sample can be found in that paper; here we give a brief overview. Our sample is drawn from the Galaxy And Mass Assembly survey II (GAMA; Driver et al. 2009, 2011), the largest homogeneous multi-wavelength dataset currently available, in terms of both spatial volume and wavelength coverage. GAMA is primarily a redshift survey, but it is supplemented by a highly consistent and complete set of multi-wavelength data, spanning from the far-UV to radio.

The GAMA imaging data includes five-band optical (ugriz) imaging from SDSS (York et al. 2000) and four-band near-infrared (YJHK) imaging from the Large Area Survey (LAS) component of the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). All of these bands have a depth and resolution amenable to Sérsic-profile fitting (as demonstrated by Kelvin et al. 2012). Conveniently, the images for all nine bands have been "micro-registered" onto the same pixel grid (using SWarp, Bertin et al. 2002; Bertin 2010) as described in Hill et al. (2011), and rescaled to a common zero point of 30 mag, which are essential for our purposes.
Our sample is limited to galaxies in one region of GAMA, the equatorial field at 9h R.A. (known as G09). The multi-wavelength imaging data provided by GAMA is analysed using a modified version of GALAPAGOS (Barden et al. 2012). This version (galapagos-2) has been adapted for use on multi-wavelength, ground-based data, as described in detail in H13. This software enables the automated measurement of wavelength-dependent Sérsic profile parameters for very large samples of galaxies in a homogeneous and consistent manner. To fit each galaxy, galapagos-2 utilizes a recently-developed multi-wavelength version of Galfit (which we refer to as Galfitm). This extended version of Galfit was introduced in H13 and is described in detail in Bamford et al. (in prep). We refer the interested reader to this paper and H13 for further details and technical background reading.

Galfitm fits a single wavelength-dependent model to all the provided images simultaneously. Rather than fit the parameter values at the wavelength of each band, Galfitm fits the coefficients of a smooth function describing the wavelength dependence of each parameter. Specifically, Galfitm employs Chebyshev polynomials, with a user-specifiable order for each parameter, which controls the desired smoothness of their wavelength dependence. For example, the $x$ and $y$ coordinates of the galaxy centre may be allowed to vary, but remain a constant function of wavelength. Magnitudes could be allowed to vary completely freely, by setting a sufficiently high polynomial order. Other parameters may be allowed to vary at a lower order, providing flexibility to obtain a good fit, while avoiding unjustified (physically or by the data quality) variability and reducing the dimensionality of the model.

In the fitting process for this paper, we allow full freedom in magnitudes, while Sérsic index and $R_e$ are allowed to vary with wavelength as second order polynomials. All other parameters ($x$ and $y$ position, position angle and axis ratio) are selected to be constant with wavelength.

Amongst other data, galapagos-2 returns magnitudes ($m$), Sérsic indices ($n$) and effective radii ($R_e$), calculated at the wavelength of each input image. To investigate the reliability of our size determinations, we have compared our $R_e$ measurements to an alternative, less model-dependent, estimate of galaxy size. Specifically, Galfitm employs Chebyshev polynomials, with a user-specifiable order for each parameter, which controls the desired smoothness of their wavelength dependence. For example, the $x$ and $y$ coordinates of the galaxy centre may be allowed to vary, but remain a constant function of wavelength. Magnitudes could be allowed to vary completely freely, by setting a sufficiently high polynomial order. Other parameters may be allowed to vary at a lower order, providing flexibility to obtain a good fit, while avoiding unjustified (physically or by the data quality) variability and reducing the dimensionality of the model.

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Figure 1. Comparison between the effective radius in $r$-band obtained by Galfitm and the radius containing half the flux within the Kron aperture in $r$-band, for the galaxy sample described in §4.2. Red crosses: galaxies with $n_r > 2.5$. Blue dots: galaxies with $n_r < 2.5$. Dashed line represents the 1:1.

derive a continuous function of wavelength. On high S/N data, for single-component fits, this would give more or less equivalent results to our approach. However, on lower signal-to-noise images our approach is substantially more robust (H13, Vika et al. 2013, Bamford et al. 2013). Nevertheless, there are cases where directly using the fit polynomial function to interpolate between bands is inadvisable.

If a high degree of freedom is given to a certain parameter (e.g. magnitude in our case), the polynomial may oscillate between the wavelengths at which it is constrained by data, and especially in regions close to the edge of the wavelength range of the input data. This is a general issue encountered when fitting polynomials, known as ‘Runge’s phenomenon’. As a consequence, we do not use the polynomial derived for the magnitudes to directly calculate rest-frame magnitudes for all objects. Instead, we recommend using the magnitudes derived for each input band to accurately estimate rest-frame magnitudes and colours using a stellar population fitting code.

2.2 Our galaxy selection

We match our sample to the GAMA redshift catalogue (SpecObjv21). For the galaxies in the catalogue, we compute absolute magnitudes by applying INTERREST (Taylor et al. 2009) to our measured photometry. This tool determines rest-frame colours by interpolating the observed photometry, using a number of template spectra as guides (for details, see Rudnick et al. 2003).

For Sérsic index and effective radii, the polynomial order is sufficiently low that Runge’s phenomenon is not an issue. We can therefore conveniently calculate rest-frame values directly using

\begin{itemize}
\item $n_r > 2.5$
\item $n_r < 2.5$
\end{itemize}
the respective Chebyshev functions returned by \texttt{galfitm}, provided the required wavelength is in the range covered by the input data. For the remainder of this paper, all mentions of wavelength, or ‘band’, refer to rest-frame quantities, unless explicitly stated otherwise.

As in H13, the catalogue resulting from \texttt{galapagos}-2 has been cleaned in order to select only the objects that have been successfully fit by \texttt{galfitm}. In particular, we wish to identify and discard fits with one or more parameters lying on (or very close to) a fitting constraint. Such a fit is unlikely to have found a true minimum in $\chi^2$ space and is indicative of a serious mismatch between the model profile and the object in question. The selection also serves to remove stars from the catalogue. Following H13, we extract those galaxies that satisfy the following criteria:

- \( 0 < m < 40 \) at all wavelengths, where \( m \) is the total apparent output magnitude in each band.
- \( m_{\text{best}} - 5 < m < m_{\text{best}} + 5 \), where \( m_{\text{best}} \) is the starting value of the magnitude in each band. These are derived by scaling an average galaxy SED (obtained from previous fits) by the \texttt{galfitm} best value measured by \texttt{SExtractor} during the object detection. As it is known (e.g., Hauder et al. 2007) that \texttt{galfitm} is very stable against changing the starting values, such an approach is valid and was easy to implement into \texttt{galapagos}-2 (see H13 for details). During the fit, we allow a generous \( \pm 5 \) magnitudes variation from these starting values.
- \( 0.201 < n < 7.99 \), since fits with values outside these ranges are rarely meaningful [Vika et al. 2013] though note that some elliptical galaxies are indeed measured to have \( n > 8 \), e.g., as shown in (Caon, Capaccioli, & D'Onofrio 1993)
- \( 0.301 < R_e < 399.0 \) pixels, which maintains values in a physically meaningful range and prevents the code from fitting very small sizes, where, due to oversampling issues, the fitting iterations become very slow.
- \( 0.001 < q \leq 1.0 \), where \( q \) is the axis ratio, to ensure the fit value is physically meaningful. In practice, this constraint is barely ever encountered.

This catalogue cleaning is done on all bands simultaneously, i.e. if any value of the fit fails to meet the above criteria for any band, the entire fit is considered unsuccessful.

We additionally exclude objects with:

- \( 132.6 \leq \alpha \leq 142.0 \) and \( -1.55 \leq \delta \leq -0.50 \);
- \( 135.2 \leq \alpha \leq 135.7 \) and \( -0.35 \leq \delta \leq +0.20 \);
- \( 130.0 \leq \alpha \leq 131.2 \) and \( -2.50 \leq \delta \leq -1.20 \);

which are objects close to areas for which at least one of the infrared bands (\( YJHK \)) does not provide good data quality. The first one of these areas has no data coverage in the J-band image, the other two are close to very bright stars which caused scattered light in the image, essentially making them unusable in some of the band in these areas. Rather than fitting different galaxies using different combinations of bands, we prefer to maintain a homogeneous dataset and excluded galaxies in these areas.

\footnote{Please note that the last criterion used in H13 (95 – \( 5 \times \text{mag}_\text{best} < \text{fwhm}_\text{image} \) and \( \text{fwhm}_\text{image} < 1 \) pixel) is not used in this paper. The purpose of this cut was to separate (mainly saturated) stars from galaxies in order to derive a cleaner galaxy sample for code testing and comparing single- and multi-band fitting techniques. In this paper, this step is not necessary as galaxies are selected by a redshift criterion. Avoiding it prevents us from accidentally removing bright, compact galaxies from our sample.}

The aim of this paper is to carefully analyse how galaxy structural parameters change as a function of wavelength. We expect different types of galaxies to behave in contrasting ways. We therefore separate galaxies according to their colour and structure. Throughout the paper, we use the rest-frame \( (u-r)_f \) colour, and the \( r \)-band Sersic index, \( n_f \), as our reference for separating populations. The choice of colour is not critical. However, bracketing the 4000 Åbreak, \( (u-r)_f \) performs well for separating red and blue populations, despite the noisiness in the SDSS \( u \)-band. After some experimentation, \( n_f \) turned out to be the best choice for separating high- and low-concentration populations, which roughly correspond to early- and late-type morphologies in our luminous galaxy sample. Choosing \( (u-r)_f \) and \( n_f \) also facilitates comparison with previous SDSS studies.

Figure 3 plots colour versus Sersic index for our sample. These are clearly correlated, and the well-known bimodality (e.g., Kauffmann et al. 2003, Driver et al. 2006) is evident. Galaxies may be optimally divided into two types using a sloping cut in this plane.
However, we find it is informative to study the behaviour with respect to colour and Sérsic index in more detail, and thus apply selections to these two quantities independently. We empirically divide galaxies into red and blue using the cut $(u-r) = 2.1$. Traditionally the division by colour also includes a magnitude dependence; however, this is a small effect, particularly at the bright magnitudes considered in this paper. To avoid complicating our analysis we prefer this simple cut. In addition to separating red and blue galaxies, we are also interested in the bluest population, which may host starbursts. We therefore further subdivide the $(u-r) < 2.1$ population into ‘green’ and ‘blue’ galaxies, using a cut at $(u-r) = 1.6$. We note that our ‘green’ galaxies do not correspond to what is commonly understood as the ‘green valley’, between the blue and red modes. We simply adopt this name to describe objects with blue, but not extremely blue, colours. Henceforth we use italics to explicitly indicate when we are referring to the red, green or blue samples.

We further divide galaxies by Sérsic index, with the aim of better separating disk galaxies from ellipticals. Following previous works (e.g. [Barden et al. 2005]), we adopt a cut of $n_r = 2.5$. From now on, we will refer to ‘low-$n$’ galaxies with $n_r < 2.5$ and ‘high-$n$’ galaxies with $n_r > 2.5$.

With these combined cuts we can compare the two main galaxy populations: green low-$n$ systems, which correspond to star-forming, disk-dominated galaxies, and red high-$n$ systems, which are typically passive spheroid-dominated galaxies. We can also examine the properties of galaxies which do not respect the majority behaviour.

We caution the reader that these definitions do not extend down to the fainter dwarf galaxies. Our sample selection is limited to luminous galaxies, so trends discussed in this paper do not represent the faint population.

Table [1] summarises the fraction of galaxies corresponding to our different colour and Sérsic index selections. As expected, most red galaxies ($\sim 70\%$) are characterised by large values of Sérsic index, while the vast majority of blue ($\sim 82\%$) and green galaxies ($\sim 73\%$) display small values of Sérsic index.

In the next section we study how the structural properties of galaxies, characterised by different colours and surface brightness profiles, vary with wavelength.

### 3 RESULTS

Trends in galaxy properties with wavelength may be studied from two perspectives. One can investigate correlations for an entire galaxy population, or measure variations in individual galaxies. The first approach is useful when the variations in individual galaxies are noisy. Combining large samples allows one to identify trends which would be obscure for individual objects. Such population trends do not guarantee that galaxies individually follow the average trend, but they can place constraints on the range of variation for individual galaxies. Averaged trends also do not allow one to easily select subsamples with specific properties. The second approach is possible when one has sufficiently reliable measurements. In this case it is preferable to study the distributions of those measurements directly. In this way, one can examine how consistent the trends are across the galaxy population and isolate subsamples with different behaviour.

We first consider trends in Sérsic index and effective radius versus wavelength, averaged across various subsets of the galaxy population. We then consider the distributions of these trends for individual galaxies. These individual measurements allow us to study correlations of the trends with other quantities, and consider their use in classifying galaxies. We show that the population trends, like those presented by [La Barbera et al. 2010b] and [Kelvin et al. 2012], do successfully capture the typical wavelength variation of Sérsic index and effective radius in individual galaxies. Finally, we investigate the correlations between wavelength variations in Sérsic index and effective radius, finding highly contrasting behaviour for early- and late- type galaxies.

This section will focus on presenting the observed variation of Sérsic index and effective radius and their respective ratios at different wavelengths. First we consider Sérsic index and effective radius individually, in §3.1 and §3.2 respectively. Then, in §3.3 we examine correlations between their behaviour. In the subsequent section, §4, we will confirm the meaning of our results, and discuss their interpretation, with the aid of stacked images.

#### 3.1 Wavelength dependence of the Sérsic index

##### 3.1.1 Population trends

To begin, we examine the distribution of Sérsic index, and its variation with wavelength, for a variety of samples. We first consider the overall galaxy population divided using the colour cuts described in §2.3. These distributions are plotted for each passband in Fig. [4]. The wavelength dependence of the Sérsic index distribution for the full magnitude-limited sample of GAMA galaxies has previously been presented by [Kelvin et al. 2012], based on independent fits to each band. Kelvin et al. also divide into spheroid and disk dominated systems using a joint cut on $(u-r)$ and $n_k$. Here we show in Fig. [4] a volume-limited sample with measurements obtained using our multi-band method, meaning that we have measurements in every band for the whole sample. Furthermore, unlike [Kelvin et al. 2012]...
Figure 4. Sérsic index distribution for our full sample (black line) and for galaxies in each of our colour subsamples (red, green, blue). Each panel shows the distribution in a different band: $ugrizYJH$. The median of each distribution, and its uncertainty, are indicated by vertical solid and dashed lines, respectively. The median Sérsic index for red galaxies does not depend on wavelength, while for our green and blue subsamples the Sérsic index increases significantly toward redder wavelengths.

As it is well known, and also as seen in Fig. 4, galaxies of different colour are characterised by very different Sérsic index distributions: the median Sérsic index across all wavelengths is $3.39 \pm 0.07$, $1.8 \pm 0.3$ and $1.4 \pm 0.2$ for red, green and blue galaxies, respectively. The quoted uncertainties on the median are estimated as $1.253\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation about the median and $N$ is the number of galaxies in the sample under consideration (Rider 1960).

In addition to their different medians, Fig. 4 shows that the blue and red samples are skewed in opposite directions. The green sample follows the same distribution as the blue sample at low-$n$, but has a higher proportion of high-$n$ objects. Galaxies of different colour thus dominate at different Sérsic indices. Colour is therefore a reasonably good predictor of galaxy structure, and vice versa. However, remember that often we wish to study colour (e.g., as an indicator of star-formation history) versus galaxy structure, and so frequently need to identify galaxies with contrasting structure without reference to their colour. Also, note that there is a significant region of overlap at intermediate Sérsic index, where the majority of galaxies are found.

The overall distribution becomes more strongly peaked and moves to higher values of $n$ with increasing wavelength. A similar trend is observed for each of the red, green and blue subsamples. However, whereas the whole distribution shifts for blue and green galaxies, the only change for red galaxies is a slight decline in the proportion of low-$n$ galaxies. The median $n$ for red galaxies is therefore almost perfectly constant with wavelength, while the medians for the bluer samples vary significantly. Many blue galaxies must significantly change appearance from the $u$- to the $H$-band.

Having examined the full distributions in Fig. 4, we present the variation in median Sérsic index as a function of wavelength more compactly in Fig. 5. The lack of variation in Sérsic index with wavelength for red galaxies indicates that they principally comprise one-component objects, i.e. elliptical galaxies, or two-component galaxies in which the components possess very similar colours, i.e. lenticulars. In contrast, the systematically lower values and more substantial trends exhibited by green and blue galaxies are consistent with them being two-component systems, comprising both a blue, low-$n$ disk and red, high-$n$ bulge, with the disk being more dominant for bluer galaxies. Of course, various other types of galaxies may be present in the galaxy population, e.g. spi-
However, the correlation is not perfect, as is clear from Fig. 3. As described in MacArthur et al. 2004), however, it is not clear whether such gradients would manifest themselves as variations in the disk stellar population (i.e. age and metallicity) with radius (as found by de Jong 1996b; Beckman et al. 1996; Pompei & Natali 1997; Waller et al. 2003; MacArthur et al. 2004). However, it is not clear whether such gradients would manifest themselves as variations in Sérsic index with wavelength.

We remind the reader that in the above analysis we have not applied any cut in $n$: a cut in the colour-magnitude plane results in a natural separation of galaxies with small and large Sérsic index. However, the correlation is not perfect, as is clear from Fig. 3. As previously mentioned, Kelvin et al. 2012 address this by defining a joint cut in $(u - r)$ versus $n_k$ to divide all galaxies into one of two classes. We build on their analysis by taking a complementary approach. Objects with combinations of colour and Sérsic index contrary to the majority, e.g., red spirals and blue ellipticals, potentially correspond to interesting stages of galaxy evolution. Studying these may illuminate the physical processes responsible for the structural evolution of galaxies. We therefore proceed by considering subsamples defined by independent cuts in both colour and Sérsic index, as described in §3.2.

Figure 6 shows the dependence of median Sérsic index on wavelength for these six different populations. The different behaviour of galaxies with low and high Sérsic index is striking. High-n galaxies consistently display much less Sérsic index variation with wavelength than low-n galaxies. Red, high-n galaxies show no significant dependence on wavelength (in agreement with the results of La Barbera et al. 2010b for early-type galaxies). The median value across all wavelengths is $4.10 \pm 0.09$. Therefore, on average, they possess a classic de Vaucouleurs profile at all wavelengths. Green and blue galaxies with high-n show a mild dependence on wavelength. Both have a median Sérsic index of $\sim 3.5$, and are equal in the $r$-band. However, the median $n$ for blue (high-n) galaxies decreases toward redder wavelengths (the Pearson product-moment correlation coefficient is $r = 0.98$, indicating a high significance), while green (high-n) galaxies show the opposite trend, increasing toward redder wavelengths ($r = 0.8$, significant at the 99% level). This interesting contrast, which is also seen for individual galaxies in the next section, is our main motivation for considering green and blue galaxies as separate samples.

For low-n galaxies, the median Sérsic index shows a substantial trend with wavelength, increasing from the $u$- to $H$-band. The median Sérsic index and the strength of its variation with wavelength depend on the colour of the population considered. The median value systematically increases from blue to green to red galaxies, while the trend of the strength of wavelength is similar for blue and green samples, but shallower for red galaxies. Comparing to Figure 5, it is apparent that a cut only in colour mixes populations and thus loses useful information. Blue and green galaxies with high-n actually show similar trends to the overall population, although they number too few to influence the trends when no cut in Sérsic index is applied. Similarly, the trend for red galaxies with low-n resembles those of blue and green galaxies. Low-n galaxies make up a significant proportion of the red population, and thus they substantially reduce the median value of red galaxies when Sérsic index is not taken into account. The degree of variation of Sérsic index with wavelength is more closely related to the overall value of Sérsic index than to colour.

The adopted Sérsic index cut at $n_i = 2.5$ does not appear to significantly alter the trends we recover for the low-n and high-n populations. The $n_i$ distributions for each colour sample are sufficiently distinct and narrow that only a small fraction of each distribution is affected by the Sérsic index cut. This is apparent from the observations that the standard deviations of the red and green distributions only just cross in Fig. 5 and the average of the red, low-n sample in Fig. 6 extends to almost $n_i = 2.5$ in the $H$-band, without any sign that the trend is being suppressed. Given that our subsample definitions are based on Sérsic indices in only one band ($r$), it is also reassuring to note that the spheroidal population retains high Sérsic index values across all wavelengths. This indicates that performing the Sérsic index separation in different bands would not substantially affect the samples, nor the above results. However, Fig. 6 does suggest that separating in bluer bands, where the populations are better separated, is advisable.

### 3.1.2 Sérsic index versus wavelength for individual galaxies

The analysis we have presented so far considered average trends across a sample of galaxies. If all galaxies in a given sample behave in the same way, then the trends in the average do reflect the trends in the individual galaxies. However, there is the possibility that individual galaxies have behaviours which cannot be easily identified from the distributions of Sérsic index in different bands. For example, if the average $n$ for a sample does not change between two bands, it could be that all the constituent galaxies have constant $n$, but it is also plausible that half the galaxies increase their $n$ while the other half decrease, or that most remain constant while a minority display a significant trend, etc. We have already seen such behaviour when dividing by colour: different trends have
been revealed for particular subsamples. In this case we were able to discover this by dividing by Sérsic index, but ideally we would like to look for such trends directly in the full sample.

In this section we aim to explore the wavelength dependence of Sérsic index for individual galaxies. This is difficult when fitting galaxies independently in each band. However, as shown by H13, our multi-band method dramatically reduces the noise on such measurements and avoids cases where galaxies are successfully fit in some bands, but not in others.\footnote{We have confirmed this by making versions of the figures in this paper based on single-band fits. These all contain dramatically fewer objects which pass our quality control cuts, and the distributions show much larger scatter.}

We thus have measurements of Sérsic index in every band for all objects in our sample. With this information it is possible to devise various ways of quantifying the wavelength dependence of Sérsic index. In this paper we take the conceptually and computationally simple approach of comparing values at particular pairs of wavelengths, by taking their ratio. We will investigate what these ratios can tell us about the correlations between galaxy stellar populations and spatial structure.

For compactness we adopt the notation $N_{H}^{r} = n(r)/n(b)$, where $n(r)$ and $n(b)$ are the Sérsic indices in some (rest-frame) red and blue band, respectively (we thus generally maintain the same convention as colour). Using a ratio, rather than a difference, is appropriate, as the physical distinction between profiles separated by constant $\Delta n$ decreases for larger $n$; i.e. there is more ‘difference’ between $n = 1$ and $n = 1.5$ profiles, than between $n = 4$ and $n = 4.5$ profiles. This is the same reason why $n$ is usually plotted with a logarithmic scale. However, the use of a ratio results in asymmetric behaviour when plotted linearly: low ratios are confined to between 0 and 1, while high ratios may extend to infinity. To avoid this we usually plot $N$ on a logarithmic scale. These choices result in distributions that look much more symmetrical and Gaussian than otherwise, justifying our approach.

We begin by inspecting how galaxy colour varies with $N$, and specifically focus on the dependence of $(u-r)$ on $N_{H}^{r} = n_{H}/n_{g}$. This combination of bands ($H$ and $g$) is favoured here, and throughout the paper, as it is the pair with the longest robust wavelength baseline ($u$ is noisy and $K$ is extrapolated).

The left panel of Fig. 7 shows that the colour bimodality is accompanied by a shift of the blue population to higher values of $N_{H}^{r}$ than the red population. The remaining two panels divide the sample by Sérsic index, and demonstrate that low-$n$ and high-$n$ galaxies display different distributions in this diagram. For low-$n$ galaxies, which span a wide range of $(u-r)$, the median $N_{H}^{r}$ at any colour is greater than one. This agrees with the low-$n$ sample being disk galaxies, comprising a blue $n = 1$ disk and red $n > 1$ bulge, such that the disk is more prominent in $g$ than in $H$. Although subtle, a curve is apparent in the median $N_{H}^{r}$ versus $(u-r)$. Low-$n$ galaxies with intermediate colours have the greatest variations of Sérsic index with wavelength, consistent with the bulge and disk being of similar prominence, but differing colour, in these systems.

In contrast, the high-$n$ galaxies, which are mostly red, display a distribution that is centred on $N_{H}^{r} \sim 1$, indicating that the profile of these galaxies is similar at all wavelengths. There is a tail of high-$n$ galaxies to blue colours, which tend to have $N_{H}^{r} < 1$. This suggests that blue, high-$n$ galaxies have peakier profiles at blue wavelengths, possibly indicating the presence of a central starburst.

The segregation of galaxy populations seen in Fig. 7 suggests that $N$ could be used as a proxy to separate galaxy types or identify specific populations. For example, ‘red spirals’, disk galaxies with suppressed star-formation, should possess a disk with similar colour to their bulge. They may therefore be isolated from early-type spirals, with comparable colour and Sérsic index, by their lower $N$.

However, we reiterate that our definitions of blue versus red and low-$n$ versus high-$n$ depend on our sample selection and adopted magnitude cut. Our present results are therefore limited to the intrinsically bright galaxy population.

So far we have focused on $N_{H}^{r}$, but now we consider other combinations of bands, keeping $g$ as our reference, to be sure that our conclusions are not driven by a particular choice of the bands. Figure 8 shows the distributions of $N_{g}^{r}$, $N_{r}^{g}$, $N_{g}^{H}$, $N_{r}^{H}$. We chose to show $u$, $z$ and $H$ as examples because they are the bluest, an intermediate and the reddest bands, respectively, and $r$ because it is the band we use to define our low-$n$ and high-$n$ samples. As well
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Figure 8. Distributions of $N$ for a representative selection of bands. The four groups of panels show (1) $N^u_g$, (2) $N^r_g$, (3) $N^z_g$ and (4) $N^H_g$. Within each group, the upper panel (a) shows the distribution of $N$ for the sample overall and divided by colour, without taking into account the Sérsic index. The lower windows show the normalised histograms of $N$ for low-$n$ and high-$n$ galaxies, for red (b), green (c) and blue (d) samples separately.

The distributions are unimodal, with widths that strongly depend on the passbands involved: the redder the wavelength (relative to $g$), the broader the distributions. This is somewhat inevitable given that observations at neighbouring wavelengths will be dominated by the same stellar population, while longer wavelength baselines permit greater variability. In addition, the Sérsic index has been constrained to vary as a smooth polynomial, which will act to suppress large variations between neighbouring bands. Focusing only on colours (upper subpanels), $N$ for red galaxies always remains close to one, as does $N$ for blue and green galaxies for short wavelength baselines. Increasing the wavelength range spanned ($g$ versus $z$- and $H$-bands), blue and green galaxies have systematically higher $N$ than red galaxies, and are thus easier to differentiate, despite the increasing width of the the $N$ distributions.

Further separating galaxies for $n$ (lower subpanels), we see that the low-$n$ and high-$n$ normalised distributions differentiate, at any fixed colour. As for colour, the difference between low-$n$ and high-$n$ is more evident with longer wavelength baselines. For red galaxies the width of the $N$ distributions are very similar for low-$n$ and high-$n$ galaxies, at any wavelength. However, for green and blue objects the high-$n$ distribution is significantly broader than for low-$n$, particularly for long wavelength baselines. Objects with high Sérsic index and blue colours appear to be a varied population, although the bluest examples are rare, and hence their distribution is uncertain.

We note that at any wavelength, green high-$n$ galaxy trends resemble those of red high-$n$ galaxies, while green low-$n$ galaxy trends resemble those of blue low-$n$ galaxies, further indicating that our green sample mixes objects with different structural properties.

To assess the differences between the different distributions, we perform a Kolmogorov-Smirnov (K-S) test on each pair. The K-S tests indicate that all the subsamples are drawn from different parent $N$ distributions, except for blue and green galaxies with low-$n$, suggesting that these galaxies share common properties.

As was done for Sérsic index in Fig. 6 we show the variation in median $N$ as a function of wavelength, $\lambda$, more compactly in Fig. 9. All the ratios are normalised to the $g$-band. Points represent the median of the $N^x$ values for the galaxies in each subsample, where $x$ is the band corresponding to wavelength $\lambda$. For comparison, the lines in this figure show the ratio of the median $n(g)$ to the
median $n(x)$ (as individually plotted in Fig. 9). One can see that, as expected statistically, the median $N$ reveals the same behaviour as considering the ratio of the median trends in $n$. Fig. 9 is therefore an alternative way of presenting Fig. 8. The unimodality of the distributions in Fig. 8 and the consistency shown in Fig. 9 support the use of population trends to study the variation of galaxy structure with wavelength. However, remember that the $N$ quantifies the dependence of Sérsic index on wavelength for individual galaxies in a robust manner.

Galaxies with different Sérsic indices and colours follow different trends. For green and blue galaxies with low-$n$, $N$ correlates strongly with wavelength, such that a Sérsic index is higher at redder wavelengths. Red, low-$n$ galaxies display a weaker correlation with wavelength, while for green, high-$n$ objects it is weaker still, and entirely absent for red, high-$n$ galaxies. Finally, for high-$n$, blue galaxies $N$ anti-correlates with wavelength. This behaviour is consistent with a progression from galaxies containing significant red bulge and blue disk components, to bulge-disk systems that are increasingly dominated by a red bulge, or contain components with less contrasting colours, to galaxies possessing a single component, or homogeneous colour, and finally to systems with a bulge bluer than their disk.

As mentioned earlier, the relative prominence and colour of bulges and disks are unlikely to completely explain the trends we see. Even in pure exponential disk systems, dust attenuation can result in measured Sérsic indices that vary with wavelength. In Fig. 9 we overplot the wavelength dependence of $N$ expected for a disk population due to the effects of dust, as predicted by Pastrav et al. (2013). We do not plot the prediction for the $n$-band since we have not calculated the model for this wavelength. The black dashed line represents the wavelength dependence of $N$ for a disk population due to the e-folding or half-light, radius is simply a measure of the size, and references therein). It will be interesting to explore this result over a wider luminosity range. However, our sample is limited to intrinsically luminous galaxies, and such a conclusion would be at odds with the established magnitude-Sérsic index relation for elliptical galaxies (e.g., Graham & Guzmán 2003 and references therein). It will be interesting to explore this result over a wider luminosity range. Finally, we note again that blue high-$n$ objects tend to have $N_H^H > 1$, and hence become more concentrated at bluer wavelengths, indicative of central star-formation.

Many of the results in this subsection echo those we found earlier by considering the population trends, which are less reliant on multi-band fits. However, by reliably measuring the wavelength dependence of Sérsic index, $N$, for individual galaxies we are able to study the distribution of $N$, rather than simple averages, and even select objects with contrasting $N$ values.

Next we consider the wavelength dependence of the effective radius in a similar manner to above, before considering the joint behaviour of $n$ and $R_e$.

### 3.2 Wavelength dependence of the effective radius

#### 3.2.1 Population trends

The effective, or half-light, radius is simply a measure of the size, and thus not normally considered to represent galaxy structure directly. However, the amount by which the size of a galaxy varies
can be due to its inclination, and hence it depends on the opacity, or to its internal structure. In particular, depending upon the wavelength considered, it reveals radial variations of colour, and hence stellar population or attenuation, within a galaxy. These may be related to the presence of multiple structural components with different colours, e.g., a red bulge and blue disk, or gradients within a single structural element.

In this section, following the same approach as above for Sérsic index, we investigate how $R_e$ varies with wavelength for galaxies divided by colour and Sérsic index, as described in §2.3.

Figure 11 shows the distribution of $R_e$ in each waveband, for the full galaxy sample and for our three colour subsamples. In contrast to $n$ (Fig. 4) the distribution of $R_e$ does not depend strongly on galaxy colour. The median and shape of the $R_e$ distribution are very similar for the three samples in all wavebands.

The median $R_e$ decreases toward redder wavelengths. This behaviour is slightly more pronounced for the red sample. This is more apparent in Fig. 12, where the dependence of the median effective radius on wavelength is presented more compactly. The slope of the relations is similar for galaxies of different colour, just slightly steeper for red galaxies. Red galaxies also have a smaller median $R_e$ at all wavelengths, while blue and green galaxies show very similar values. The median $R_e$ in $u$-band are $6.4 \pm 0.1$, $7.2 \pm 0.3$ and $7 \pm 1$ kpc for red, green and blue subsamples, respectively. In $H$-band the corresponding figures are $3.94 \pm 0.09$, $4.9 \pm 0.1$ and $4.8 \pm 0.3$ kpc.

In contrast to colour and Sérsic index, in our sample there is no obvious separation of populations in effective radius. We therefore do not attempt to consider samples divided by $R_e$, but continue to use $n$ to isolate bulge- and disk-dominated populations.

Figure 13 shows the dependence of the median effective radius on wavelength for galaxies characterised by different colour and Sérsic index. Each population shows a decrease in effective radius toward redder wavelengths. Galaxies with high-$n$ are characterised by a steeper trend ($a \sim 45\%$ reduction in $R_e$ from $u$ to $H$) than those with low-$n$ ($\sim 25\%$ reduction). The three low-$n$ samples behave very similarly; the variation of median $R_e$ with wavelength does not depend on colour for low-$n$ galaxies. The high-$n$ samples display more variety, with bluer galaxies showing a stronger wavelength dependence.

### 3.2.2 Effective radius versus wavelength for individual galaxies

Following the same reasoning and approach for Sérsic index, we now move to quantifying the dependence of effective radius on wavelength for individual galaxies. We adopt the similar notation $R_e^u = R_e(u)/R_e(b)$, where $R_e(u)$ and $R_e(b)$ are the effective radii in some (rest-frame) red and blue band, respectively (again maintaining the standard colour convention where sensible). Using a ratio is appropriate, as we are more interested in fractional, rather than absolute, variations in $R_e$. As with $N_e$, to avoid an asymmetry when plotting $R_e$, we use a logarithmic scale. The resulting distributions appear symmetrical and approximately Gaussian.

To start, we examine the relationship between galaxy colour ($u - r$) and $R_e^u = R_e(H)/R_e(g)$ in Fig. 14. This displays similar behaviour to the distribution of $(u - r)$ versus $N_e$ Fig. 7. The distribution of $R_e^u$ is different for galaxies on either side of the usual colour bimodality, and the two overlapping modes can be well separated by dividing by Sérsic index. Low-$n$ galaxies occupy a narrow vertical locus, indicating that they can assume a wide range of colours, but are limited to a narrow range around $R_e^u \sim 0.8$. In contrast, high-$n$ galaxies, which have preferentially red colour, display a broader distribution offset to lower $R_e^u \sim 0.6$. Bluer high-$n$ galaxies are offset to even lower $R_e^u$. As with $N_e$, this figure indicates that galaxies of different Sérsic index have $R_e$ with different wavelength dependence, suggesting that $R_e$ could be useful for classifying galaxies.

We now compare the $R_e$ distributions for various combinations of bands, keeping $g$ as our reference, for our full sample of galaxies and subsamples divided by colour and Sérsic index, as described in §2.3. Figure 15 shows that galaxies of different colours show...
Wavelength-dependent sizes and profiles of galaxies

Figure 14. Density map of \((u - r)\) colour versus the ratio of the \(H\)-band effective radius and \(g\)-band effective radius, defined here as \(R_{eH}/R_{eg}\). The left panel considers all galaxies together, while centre and right panels show only galaxies with low and high Sérsic index respectively. The median \(R_{eH}\) as a function of colour is also plotted, for both the low-\(n\) (blue line) and high-\(n\) (red line) samples. The two populations show different distributions, indicating that they are characterised by different internal structures. Most galaxies have \(R < 1\), indicating that they appear smaller at redder wavelengths, with high-\(n\) galaxies showing the greatest effect.

Figure 15. Distributions of \(R\) for a representative selection of bands. The four groups of panels show (1) \(R_{eu}\), (2) \(R_{er}\), (3) \(R_{ez}\) and (4) \(R_{eh}\). Within each group, the upper panel (a) shows the distribution of \(R\) for the sample overall and divided by colour, without taking into account the Sérsic index. The lower windows show the normalised histograms of \(R\) for low-\(n\) and high-\(n\) galaxies, for red (b), green (c) and blue (d) samples separately.
very similar $R$ distributions, for any wavelength baseline. As for $N$, the distributions are unimodal, with widths that depend on the passbands involved: the longer the wavelength baseline, the broader the distributions. The medians of these distributions become lower for longer wavelength baselines. Focusing on galaxies with low-$n$ and high-$n$, we find that low-$n$ galaxies are characterised by an $R$ distribution which is completely independent of colour and varies only slightly with wavelength baseline. In contrast, the median $R$ for high-$n$ galaxies depends on colour, becoming lower for bluer galaxies. Similar to $N$, the $R$ distribution for high-$n$ galaxies is typically broader than for low-$n$ galaxies.

We summarise the median trends of $R$ versus wavelength in Fig. 16. Points represent the median of the $R_x$ values for the galaxies in each subsample, where $x$ is the band corresponding to wavelength $\lambda$. For comparison, the lines in this figure show the ratio of the median $R_x(g)$ to the median $R_x(x)$ (as individually plotted in Fig. 13). As before, thanks to the simplicity of the distributions in Fig. 15 these two approaches give equivalent results.

Galaxies with low-$n$ and high-$n$ clearly display different trends: the former show a relatively mild decrease in $R$ with wavelength, which is indistinguishable for the three colour samples. Low-$n$ galaxies are characterised by very similar size distributions at any wavelength, regardless of their colour. In contrast, trends for high-$n$ galaxies are more pronounced and become steeper for bluer samples. Blue, high-$n$ galaxies decrease in effective radius by over a factor of two from $u$- to $H$-band.

Figure 16 also plots the wavelength dependence of $R$ predicted for a disk population, due solely to the effect of dust attenuation, as computed in Pastrav et al. (2013) from the radiative transfer model simulations of Popescu et al. (2011). Their prediction is significantly flatter than our disk-like (low-$n$) points, suggesting that only part of the slope we measure might be ascribable to the presence of dust. Note that, although the model of Popescu et al. (2011) contain colour gradients, here we only plot the wavelength dependence due to dust alone. While the trends for disk galaxies may be due to their two-component nature, the strength of our high-$n$ trends indicate that this subsample comprises galaxies with strong colour gradients. These may be due to multiple components with different SEDs, or substantial stellar population or dust gradients within a single structural component (Pastrav et al. 2013).

3.3 The joint wavelength dependence of Sérsic index and effective radius

So far, we have considered the wavelength dependence of Sérsic index, $N$, and effective radius, $R$, separately. Summarising the results obtained from Figs. 7 and 13 we find that low-$n$ galaxies, which can assume a wide range of colour, mostly have $N$ above one ($\langle N_N \rangle \sim 1.5$; $0.8 \leq N_N \leq 3$) and occupy a narrow $R$ range ($\langle R_H \rangle \sim 0.8$; $0.5 \leq R_H \leq 1.1$). At redder wavelengths they therefore typically display smaller and peakier (higher $n$) profiles. This is consistent with low-$n$ galaxies typically being bulge-disk systems, comprising a small, $n \geq 2$, red bulge and larger, exponential, blue disk. However, dust may also play a role in these trends.

In contrast, high-$n$ galaxies, which span the full range of colour but are preferentially red, have $N$ centred on unity ($\langle N_H \rangle \sim 1.0$; $0.5 \leq N_H \leq 2.0$), and $R$ offset to slightly lower values ($\langle R_H \rangle \sim 0.6$; $0.3 \leq R_H \leq 1.1$). At the reddest wavelengths their profiles typically maintain the same shape ($n$) but become substantially smaller. This is initially surprising, as a stellar population gradient would, in general, be expected to result in both the Sérsic index and effective radius varying with wavelength. Our high-$n$ galaxies are consistent with comprising either a single spheroidal structural component with a strong stellar population gradient, or multiple spheroidal components with different $R$, and stellar populations, such that the larger components have bluer colours. The former may be identified with a single monolithic collapse, for which the colour gradient would be driven by metallicity. The latter may correspond to distinct phases of collapse or merging.

We can generalize our findings for $N_H$ and $R_H$ by considering $N$ and $R$ for multiple wavebands. Figure 17 shows how the median of the $N$-$R$ distribution varies with wavelength for galaxies belonging to each of our six subsamples, and neatly presents many
of the trends we have explored above. Low-\(n\) and high-\(n\) galaxies show different behaviour with respect to wavelength: low-\(n\) galaxies vary substantially in \(N\), but over only a narrow range in \(R\). On the other hand, high-\(n\) galaxies vary widely in \(R\), but only slightly in \(N\). Colour has a more subtle influence on these trends. For low-\(n\) galaxies, redder galaxies vary less in \(N\), but equally in \(R\). High-\(n\) galaxies show a particularly interesting behaviour with colour. Red galaxies, which comprise the majority of the high-\(n\) population, show almost no variation in \(N\), but vary significantly in \(R\). Green high-\(n\) galaxies show a slight increase in \(N\) with wavelength, potentially indicating the presence of a blue disk, but show an even greater variation in \(R\), in contrast to the low-\(n\) objects. Blue high-\(n\) galaxies continue the trend of a strengthening wavelength dependence for \(R\), but reverse their behaviour in terms of \(N\), appearing peakier at shorter wavelengths. The trends with wavelength are relatively linear in \(N\) versus \(R\). They are therefore well-described by any one pair of wavebands, justifying our approach of focussing on \(H\) and \(g\) throughout this work.

3.4 \(N\) and \(R\) as a classifier

Above we find, somewhat unsurprisingly, that the wavelength-dependence of low-\(n\) galaxies is consistent with them containing both a spheroid and disk, while high-\(n\) galaxies comprise one or more spheroidal components. This allows the possibility of using \(N\) and \(R\) to directly identify bulge-disk systems, irrespective of their overall colour or Sérsic index. Furthermore, we can combine information from \(N\) and \(R\) with colour and Sérsic index to isolate galaxies with specific structural properties. We now briefly investigate the use of \(N^{th}_{\text{eff}}\) and \(R^{th}_{\text{eff}}\) alone to separate galaxy populations with distinct internal structure.

In Fig. 18 we consider the main contrasting populations: blue low-\(n\) galaxies and red high-\(n\) galaxies. Although the averages of the two populations are significantly offset (see Fig. 17), their distributions are sufficiently broad that they overlap considerably. Blue low-\(n\) galaxies inhabit a compact locus within that of red high-\(n\) galaxies. It is therefore possible to cut the \(N\)-\(R\) plane to isolate a pure, but incomplete, sample of red high-\(n\) galaxies, but any selection of blue low-\(n\) objects will be significantly contaminated. It is not yet clear whether the breadth of these distributions is determined by measurement uncertainties or intrinsic variations. Our sample has relatively low signal-to-noise and poor spatial resolution. With higher quality data or a lower-redshift sample, it may well be that galaxy populations will separate more cleanly in the \(N\)-\(R\) plane. However, for galaxy classification \(N\) and \(R\) are best considered as complementary to Sérsic index or colour, rather than a potential replacement.

From the behaviour of the various colour and Sérsic index selected samples in the \(N\)-\(R\) plane it is certain that \(N\) and \(R\) contain additional information. For example, within red high-\(n\) objects, \(N\) and \(R\) may be used to isolate galaxies which show evidence for perhaps containing a blue disk (\(N \gg 1\)), or central star-formation (\(R \ll 1\)).

4 INTERPRETATION

Our analysis has demonstrated that the wavelength dependences of Sérsic index and effective radius are related to other galaxy properties. However, it is now helpful to pause and consider what \(N\) and \(R\) actually mean. What do galaxies with different values of \(N\) and
\( n \) primarily indicates the degree to which the central concentration of the light profile varies with wavelength. However, remember that for a given \( R_e \) a greater central concentration also implies more light in the outer regions of the profile. A value of \( n > 1 \) implies that the galaxy has a peakier (higher-\( n \)) profile in redder bands. All else being equal, galaxies with \( n > 1 \) should therefore appear redder in their centres, bluer at intermediate radii, and then redder again in their outskirts. In practice, however, the behaviour in the outskirts is often lost in the sky noise and the S/N-weighting scheme employed by \texttt{galfit} means that it cares much less about the outer profile. \( n < 1 \) implies the opposite behaviour, that galaxies are peakier in bluer bands, whereas \( n \sim 1 \) indicates that the profile has a similar shape at all wavelengths.

\( R \) quantifies the variation in size with wavelength. For example, \( R < 1 \) implies that a galaxy is smaller in redder bands. All else being equal, galaxies with \( R < 1 \) should therefore appear redder in their centres and bluer toward their outskirts. \( R > 1 \) implies the opposite behaviour, whereas \( R \sim 1 \) indicates a constant color with radius. \( R \) thus works much like a conventional colour gradient, and in the same sense, in that a negative colour gradient would imply a bluer colour with increasing radius.

Note that (considering only the behaviour at \( \lesssim R_e \)) variations in \( N \) may represent similar visual effects to variations in \( R \), but in an opposite sense (i.e. in broad terms, increasing \( N \) mimics decreasing \( R \)). However, although \( N \) and \( R \) can produce superficially the same appearance, as we have seen above they are certainly not interchangeable, providing distinct information regarding the dependence of galaxy structure on wavelength.

Figure 19 presents colour images of two galaxies. These are chosen to be bright, well-resolved objects, but are otherwise typical examples from our \texttt{red}, \texttt{high-n}, and \texttt{green}, \texttt{low-n} samples. We have examined a large number of similar images, and see that the general behaviour expected from our \( N \) and \( R \) measurements is confirmed by visual inspection.

When we compare individual galaxies with similar properties, but different values of \( R \) or \( N \), it is possible to see differences. However, this is somewhat obscured by other variations between individual galaxies, and the relatively low signal-to-noise of many

\( R \) look like, and how do they compare with the more usual concept of colour gradients?

\( N \) primarily indicates how the degree to which the central concentration of the light profile varies with wavelength. However, remember that for a given \( R_e \), a greater central concentration also implies more light in the outer regions of the profile. A value of

\( \frac{N}{N^*} \) versus \( \frac{R}{R_e} \) for blue low-\( n \) galaxies (blue points) and red high-\( n \) galaxies (red points). In the left panel the two samples are plotted together, while in the central and right panels separately plot the blue low-\( n \) and red high-\( n \) samples, respectively. These are the main contrasting populations in terms of colour and Sérsic index, and it can be seen that they also occupy different, though overlapping, loci in this plane.
Figure 20. Stacked $N_H^\dagger$ gradients, for galaxies with similar colour and Sérsic index. For each set of stacks we divide the galaxy sample into three groups, by cutting at $N_H^\dagger = 1.4$ and $N_H^\dagger = 1.9$ (see text for details). In each subplot, the top panels show the stacked images using the $H/g$ bands, the second-to-top panels show the residuals, the second-to-bottom panels show the ratio of the $H$ and $g$ residuals and the bottom panels show the radial profiles of the $H$, $g$ and $g$ residuals. Numbers in parenthesis are the numbers of galaxies used in each stack. The $H/g$ stack and residuals are displayed using the colour-preserving method of Lupton et al. (2004). The stack images have an asinh stretch, while the residual images are shown with a linear stretch. The $H/g$ residuals image has a false-colour scale, where green corresponds to equal residuals in $H$ and $g$, red indicates that the $H$ residuals are brighter than those in $g$, and blue indicates the converse. Each image is 30 pixels across. The radial profiles show the fractional difference in flux between this image stack and that of all objects in the same colour and Sérsic index subsample. It is clear that galaxies with higher $N$ are fainter and redder in the centre, but bluer at intermediate radii, and vice versa for lower values of $N$. We do not show images for blue and green high-$n$ galaxies because there are too few to produce meaningful stacked images.
of the objects in our sample. In order to demonstrate that \( R \) and \( N \) do represent true differences in the appearance of galaxies in an incontrovertible manner, we have stacked galaxies with similar properties. In this way individual galaxy-to-galaxy variations are averaged out and the signal-to-noise is improved.

Recall that Figures 17 and 18 shows that \( N \) and \( R \) are somewhat correlated, although the correlation is reduced when dividing by colour and Sérsic index. It is therefore difficult to completely separate out the behaviour of \( N \) and \( R \) in stacked images. However, given their opposing behaviour, they will tend to cancel out each other’s effect on galaxy appearance. Thus, if anything, the stacks may under-represent the individual effects of \( N \) and \( R \).

We combine the images using a 3-\( \sigma \) clipped mean, to exclude neighbouring object and atypical galaxies from the resulting stacked image. We further avoid any undue influence from outliers by applying the following limits to the objects in the stacks:

\[
\begin{align*}
& 0.70 < R < 0.85 \\
& R > 0.85
\end{align*}
\]

where \( R \) is defined by Eq. (137).

\[
\begin{align*}
& 0.70 < R < 0.85 \\
& R < 0.70
\end{align*}
\]

Each image is 30 pixels across. Galaxies with lower \( R \) are redder in the centre, and vice versa for higher values of \( R \). We do not show images for blue and green high-n galaxies because they are too few to produce meaningful stacked images.

Figure 21. Stacked \( R^H \) gradients, for galaxies with similar colour and Sérsic index. For each set of stacks we divide the galaxy sample into three groups, by cutting at \( R^H = 0.70 \) and \( R^H = 0.85 \) (see text for details). Panels are as in Fig. 20. Each image is 30 pixels across. Galaxies with lower \( R \) are redder in the centre, and vice versa for higher values of \( R \). We do not show images for blue and green high-n galaxies because they are too few to produce meaningful stacked images.
0.05 < z < 0.2; −22.5 < M_r < −21.2; 6 < R_e < 8 pixels and 1.0 < (u − r) < 3.0. We can therefore be sure that any features we see are associated with the main distribution of galaxies. So that the stack is not dominated by bright galaxies, before averaging we scale the images to the same object magnitude, and to preserve axial ratio information we rotate each image such that the galaxy’s major axis is horizontal. No scaling of the object sizes or circularisation is performed, as these operations were found to introduce artefacts due to distorting the point spread function (PSF). However, note that only galaxies with similar apparent R_e are included in these stacks.

We stack galaxies with similar colour, Sérsic index and ratio of either Sérsic index or effective radius in the H- and g-bands. In addition to our usual divisions in terms of (u − r) and n, for each set of stacks we divide the galaxy sample into three representative groups, by cutting at N_H = 1.4 and N_g = 1.9 and R_H = 0.70 and R_g = 0.85, respectively. This results in 36 stacked images. For example, one stack contains only red, low-n, mid-N_g galaxies, whereas another contains only blue, high-n, low-R_g galaxies. Each stack typically contains 10–100 galaxies. For comparison we also create stacked images for all galaxies of a given colour and Sérsic index, irrespective of N or R, for example, all red, high-n objects.

The differences between the stacked images are relatively clear. However, to further aid their comparison, for each N- or R-specific stack we subtract the stack of all galaxies with the same colour and Sérsic index. The results are presented as both Hzg residual colour images and maps of the ratio of the H and g residuals. The former retain intensity information, and therefore display variations in the total brightness or surface brightness profile between categories. The latter remove this brightness information and just present the residual variation in H − g colour with position. As a final visualisation, we azimuthally average the residual images to compare the radial profiles for H, z and g.

Figure 20 presents the behaviour of N for the common combinations of Sérsic index and colour. As expected from the above arguments, when compared to the average, galaxies with higher N are fainter and redder in the centre, but bluer at intermediate radii, and vice versa for lower values of N. In some of the stacks, particularly for high-n galaxies, the residuals are dominated by colour variations in the centre of the galaxy. For low-n galaxies the residuals are dominated by colour differences further out and are often elongated, suggesting the presence of a disk. Low (high) values of N appear to reflect the presence (absence) of a red disk, while the centre of the galaxy remains unchanged.

Figure 21 presents the same information for variations in R. Again, the behaviour is broadly as anticipated. Compared to the average, objects with lower R display redder centres, while higher R implies bluer centres. As with N, for low-n galaxies there are indications that the value of R partly reflects the presence of a disk. However, unlike N, the value of R is also strongly related to the presence of a red central component. Objects with lower R possess brighter, redder centres.

These stacks visually demonstrate that the different N and R values we have measured represent subtle but significant differences in the appearances of the galaxies.

5 DISCUSSION

In this paper we have explored how galaxy structure varies with wavelength (from rest-frame u to H), for populations selected by Sérsic index and colour, using a volume-limited sample of 14,274 bright galaxies. We measure galaxy sizes and radial profile shapes more accurately than previous studies, by utilising a new technique which fits consistent, wavelength-dependent, two-dimensional Sérsic profiles to imaging in a collection of wavebands. Using this method, we confirm that the behaviours of individual galaxies generally follow the average trends of populations of similar objects. We are also able to identify individual galaxies with a particular wavelength dependence of their structural parameters, and hence create samples of objects that are similar in this respect.

We find that both effective radius and Sérsic index typically vary with wavelength. The sizes of all types of galaxies decrease substantially with increasing wavelength, with high-n galaxies showing the greatest variation. The behaviour of Sérsic index is more sensitive to galaxy type: for high-n galaxies Sérsic index is constant with wavelength, while for low-n galaxies it varies dramatically.

We now discuss our findings in the context of other works: first comparing to similar studies on whose results we build, then considering the physical processes responsible for the trends we measure, and finally suggesting how subsequent studies of galaxy structure can help to further differentiate between models of galaxy formation and evolution.

5.1 Comparison with previous results

The SPIDER project (La Barbera et al. 2010b) has performed a careful analysis of the structural parameters of low-redshift early-type galaxies as a function of wavelength. They fit Sérsic profiles to imaging data from the same surveys as us (gri+ SDSS and YJHK from UKIDSS LAS) using a similar tool (2dphot; La Barbera et al. 2008), but fitting each waveband independently. La Barbera et al. found that, for early-types, R_e decreases by ∼ 35% from (observed frame) g to K. They attributed this variation to the presence of negative internal colour gradients, such that the light profile becomes more compact as one moves from shorter to longer wavelengths. The Sérsic indices of their objects span n ∼ 2–10, with a median of 6 for all wavebands. They find little variation of Sérsic index with wavelength. Although their average n does perhaps increase slightly (∼ 20%) from g to K, the trend is noisy and consistent with being flat.

La Barbera et al. (2010b) select their early-type galaxies as being bright (M_r < −20), having a passive spectral type and being better represented by a de Vaucouleurs profile than an exponential one. This roughly corresponds to our selection of red high-n objects, although our average values of n ∼ 4 is slightly lower than theirs. For this sample we find very similar results: a ∼ 40% increase in R_e from (rest-frame) u to H, while the Sérsic index remains stable, varying by < 5% over the same wavelength range. As La Barbera et al. point out, this behaviour is also consistent with Ko & Im (2005), Pature, Djorgovski, & de Carvalho (1998), Pature (1999) and Pature, de Carvalho, & Djorgovski (1998), the latter of which demonstrates that the behaviour of R_e corresponds to an increase in the slope of the fundamental plane with wavelength, further confirmed by La Barbera et al. (2010a) and references therein.

Kelvin et al. (2012) similarly perform two-dimensional single Sérsic fits to SDSS and UKIDSS LAS ugrizJHK images of galaxies in the GAMA survey, using GALFIT to fit each band independently. They defined two galaxy subpopulations, based on K-band Sérsic index and (u − r) rest-frame colour, and analysed the wavelength dependence of their structural parameters. They find that the mean effective radius of their early-types shows a smooth
variation with wavelength, decreasing by ~ 38% from (observed frame) g through K. Although their early-type selection is similar to ours, their sample is magnitude-limited (r ≤ 19.4). Compared to the volume-limited samples of our work and [La Barbera et al. (2010b)] it therefore contains additional low-luminosity, low-redshift and high-luminosity, high-redshift objects. Even so, the majority of galaxies in all these studies have similar luminosity ranges, and their findings are very similar. Kelvin et al. quote an increase in average Sérsic index of early-types of ~ 30% over g to K. However, as with [La Barbera et al.] the trend is rather noisy, and fairly consistent with being flat.

Kelvin et al. (2012) expand on the study of [La Barbera et al. (2010b)] by also considering the late-type galaxy population. These exhibit a more dramatic change in average Sérsic index, increasing by 52% from g to K, and a more gentle variation in effective radius, decreasing by 25% over the same wavelength range. We find an identical 25% variation in effective radius, but an even more extreme variation in Sérsic index, of ~ 100% (i.e. a factor of two) from rest-frame u to H band.

Our results are therefore in excellent qualitative agreement with those of Kelvin et al. (2012). It may be that the differing selections play a role in the detailed differences: in addition to the different luminosity ranges, the joint nK and (u − r) selection adopted by Kelvin et al. contrasts with our orthogonal n and (u − r) selections. For example, Kelvin et al. includes objects with low Sérsic index (n → 1) in the early-type sample provided they are sufficiently red. We also expect our individual measurements to display significantly less scatter, due to our multi-wavelength method (H13, Vika et al. 2013), which may help us recover smoother, more accurate trends.

Note that Kelvin et al. chose to classify galaxies using the Sérsic index in the K-band, in order to avoid any potential misclassifications due to the effects of dust attenuation. However, we assert that it is cleaner to use an optical Sérsic index for this purpose, as the separation between early and late-type galaxies is greater at shorter wavelengths.

Since our analysis is based on the same imaging, we can directly compare our results to Kelvin et al. (2012). We have tried applying their selection criteria to our measurements and find excellent agreement between the recovered trends. When averaging over a large sample, our different approaches to measuring the wavelength dependence of Sérsic index and effective radius give very similar results.

5.2 Physical implications

The patterns revealed in Fig. 17 provide important insights regarding the links between the stellar populations and internal structures of galaxies. Some of the revealed trends are rather surprising and deserve deeper investigation.

5.2.1 Early-type galaxies

For high-n galaxies, the constancy of Sérsic index with wavelength (N ~ 1), despite strong variations in effective radius (R < 1), points to very substantial differences in the stellar populations of early-types as a function of radius, but which are not associated with a change in profile shape.

Our clear result that high-n galaxies appear substantially smaller at longer wavelengths appears to largely rule out the scenario in which gas rich mergers build high-n galaxies that are a combination of an old (red), large-R$_e$ component together with a younger (blue), inner stellar component formed from the gas (Hopkins et al. 2008, 2009). If this is a significant mechanism in the formation of massive ellipticals, it must primarily occur at higher redshifts, and its signatures must be eclipsed by subsequent evolutionary processes, such as dry minor mergers (e.g., two phase galaxy formation (Oser et al. 2010).

Lower mass galaxies (both star-forming and passive) contain younger and lower metallicity stellar populations, and are therefore bluer in colour (e.g., Kaufmann et al. 2003). At later times, accreting material will fall on to the primary galaxy at higher velocities, as both the total mass of the primary and the distance from which merging galaxies originate increases with time. Stars accreted at later times relax into a more extended structure than the stars produced in the initial formation of the primary galaxy (Naab, Johansson, & Ostriker 2009). This is analogous to the preferential accretion of collisionless dark matter to the outskirts of haloes, leaving their inner profiles unchanged (Hotelis 2003, Salvador-Solé, Manrique, & Solanes 2005). Recent simulation studies have demonstrated similar behaviour for stars accreted on to galaxies during minor mergers (Cooper et al. 2013, Hilz, Naab, & Ostriker 2013). Stars added by minor mergers end up in extended Sérsic profiles resulting in a substantial increase in their effective radii for a modest increase in mass. This ‘inside-out’ growth scenario has gained widespread support as the mechanism responsible for the dramatic evolution of compact high-redshift ellipticals to their present, extended, forms (e.g., Hopkins et al. 2010).

Early-type galaxies are thus expected to comprise a compact red population of stars formed in-situ and a more diffuse, bluer population of stars formed in accreted systems. It is therefore reasonable for their effective radius to decrease with wavelength. However, as well as increasing the effective radius, the addition of surface brightness to the outskirts of galaxies would also be expected to increase the Sérsic index. Indeed, this effect is seen in previously mentioned simulations (Cooper et al. 2013, Hilz, Naab, & Ostriker 2013), and is consistent with observations of massive elliptical galaxies with high Sérsic indices (Kormendy et al. 2009). So, how can we reconcile the substantial variation in effective radius with wavelength with little or no corresponding change in Sérsic index?

The reality is that an early-type galaxy will have experienced a variety of merger events. The stars from each of these will be accreted over different ranges of radius, while in-situ stars will be somewhat redistributed, and the presence of gas may lead to the formation of stars in the galaxy centre. Adding stars in the outskirts of a galaxy increases n and increases R$_e$. Adding stars in the centre increases n and decreases R$_e$. However, adding stars at the effective radius (i.e., ~ 1 R$_e$) decreases n with no change in R$_e$. So, by adding material around R$_e$ as well as further out, it is possible to increase R$_e$ while maintaining n roughly constant. Also note that as the effective radius grows due to stellar accretion, subsequent accretion at the same physical radius (in terms of absolute distance and gravitational potential) will be closer to the effective radius, and hence will act to stabilise n. It can be easily checked that the sum of multiple Sérsic profiles spanning a range of R$_e$, but each with the same n and similar central surface brightness or total magnitude, is well approximated by another Sérsic profile with a similar value of n and intermediate R$_e$ (though this does depend somewhat on the weighting given to different radii). Measuring significant variations in R$_e$ with wavelength (R < 1), but small variations in n (N ~ 1), therefore appears to be a natural outcome of the two-stage formation scenario.
Cosmological models incorporating these various early-type evolutionary processes are now becoming available (e.g., Shankar et al. 2013). Comparing the properties of simulated populations of spatially resolved galaxies to the results of this paper will help to determine if and when each of these processes are occurring.

5.2.2 Late-type galaxies

For low-\(n\) objects, there is a substantial increase in the average Sérsic index from \((n) \sim 1\) in the blue to \((n) \sim 2\) in the near-infrared. This suggests that at short wavelengths, which are sensitive to young stellar populations, the galaxy profile is dominated by an exponential disk, while at longer wavelengths, which are more representative of total stellar mass, the surface brightness profile is steepened by the presence of a bulge.

Section[...] demonstrates that the effect of \(N > 1\) and \(R < 1\) is to produce a red galaxy centre and blue outskirts. As mentioned in the introduction, such colour gradients of disk galaxies are typically attributed to radial age profiles, in that they are younger at larger radii. Considering colour gradients in terms of the wavelength-dependence of Sérsic profile parameters gives a complementary perspective, and emphasises the association between the stellar populations and structural components of these galaxies.

The fact that low-\(n\) galaxies display only a small change in effective radius with wavelength, while showing a significant variation in Sérsic index, suggests that the bulge component in these systems is a spheroid with \(n \geq 2\), but which is not substantially smaller than the disk. This goes against conventional wisdom, but may be a result of our selection of very luminous galaxies, which are typically bulge-dominated.

The different trends in Sérsic index versus wavelength seen for red and blue/green low-\(n\) galaxies supports the interpretation of \(N\) and \(R\) in terms of a bulge and disk. Red low-\(n\) galaxies show very little variation in Sérsic index \((N \sim 1)\) because their bulge and disk components have similar red colours. Green and blue low-\(n\) galaxies show more substantial variation \((N > 1)\) because they possess a bluer disk, which contrasts with a red bulge.

Although the above argument provides a simple explanation, one must not underestimate the role of dust attenuation in driving, or at least complicating, the trends we observe for low-\(n\) galaxies. Dust attenuation can significantly modify the apparent structure of a galaxy, and introduce substantial variations with wavelength. Obscuring the central region of a galaxy shifts the balance of total flux towards larger radii, artificially increasing the effective radius and reducing the Sérsic index, particularly at shorter wavelengths. This predicted effect has been well discussed in the literature (Evans 1994; Cunow 2001; Möllerhoff, Popescu, & Tuffs 2006; Graham & Worley 2008). The effects on the recovered parameters of multi-wavelength Sérsic-model fits have been particularly studied by P nasta et al. 2013a,b, which show that while some of the behaviour we observe may be attributable to dust, their model is not able to account for all of the measured variation in \(n\) and \(R\), with wavelength.

Dust is not expected to be a dominant factor in the attenuation of light within high-\(n\) (spheroid-dominated) systems, hence variations in structural parameters with wavelength cannot be ascribed to its presence. Still, we find that these systems exhibit a larger variation in effective radius than that found in low-\(n\) (disk-dominated) systems. Given that such substantial dependences of structure on wavelength are seemingly possible from stellar population gradients alone, it is difficult to judge the importance of dust in driving the trends in low-\(n\) galaxies. Combining measurements of structural parameters versus wavelength with constraints on the mass and distribution of dust from sub-mm observations and appropriate models (e.g., Popescu et al. 2011; Smith et al. 2012) will greatly help in this regard.

Finally, it should be mentioned that another possible explanation for peculiar variations in \(n\) and \(R\), with wavelength is the interdependency between recovered Sérsic index and effective radius. A change in the Sérsic index arising due to relatively subtle unmodelled effects, e.g. a small core dust component, additional unresolved or disturbed structure in the core, the presence of an active galactic nucleus or uncertainty in the PSF, may all induce compensatory changes in the measured effective radius. However, to be responsible for the average trends we describe, which represent the behaviour of most galaxies in each subsample, such perturbations must be the norm. Future work fitting more complex multi-component models to specific galaxy samples will shed light on this issue, as well as addressing many of the science questions highlighted above.

5.3 Potential applications and further studies

In this paper we have demonstrated how the wavelength-dependence of Sérsic index \((N)\) and effective radius \((R)\) provide an alternative way of considering galaxy colour gradients, and enable a deeper appreciation of the physical origins of such gradients. For simplicity we have focussed on a sample of bright galaxies, with the added advantage that this selection demonstrates our method’s ability to recover meaningful information even for poorly resolved galaxy images. Obvious next steps are to study the variation of \(N\) and \(R\) as a function of luminosity (or stellar mass), to examine how the distinctions between galaxies of different colour and concentration (e.g., Fig. 17) are modified for lower-luminosity systems. The distribution of colour gradients, and hence \(N\) and \(R\), also varies significantly with environment (e.g., Weinmann et al. 2009), and as implied by the dramatic change in the relationship between overall colour and morphology with environment (e.g., Bamford et al. 2009). The relative behaviour of colour, Sérsic index, and their respective dependencies on wavelength will help us better understand the physical origins of the environmental trends observed (e.g., Volcani et al. 2012).

In addition to considering the overall distribution of \(N\) and \(R\) for particular galaxy samples, in this paper we have discussed using \(N\) and \(R\) to classify galaxies and identify objects with specific properties. Our approach is somewhat similar to that presented by Park & Choi (2005), which uses \((u - r)\) colour versus \((g - i)\) colour gradient space to perform a morphological classification of galaxies in SDSS. In this space, galaxies form well-separated early- and late-type branches. The location of galaxies along the branches reflects the degree and locality of star formation activity, and monotonically corresponds to a sequence in morphology. An analysis of the correspondence between \(N\), \(R\) and morphology is underway (Vika et al., in prep.), using the same small, but very well characterised, sample of galaxies studied in Vika et al. (2013). One major advantage of utilising colour gradient information is that blue early-type galaxies are separated from spiral galaxies, as the former tend to have either a nearly constant color profile or bluer cores, while the latter tend to have a red central bulge plus blue outer disk. We can make similar distinctions using the different \(N\) and \(R\) behaviour for galaxies with contrasting internal structures. Both Park & Choi and our method are capable of identifying a variety of unusual objects, such as central starbursts and passive disk galaxies.
We therefore foresee much potential in studying the occurrence of such galaxies as a function of stellar mass and environment.

Of course, another extension of this work would be to go beyond single-Sérsic profiles, to fit multiple component models. These are already starting to be used to great effect (e.g., Hudson et al. 2010; Lackner & Gunn 2013; Huang et al. 2013). Using a multi-component, wavelength-dependent model is straightforward with galfitm, and we are currently working with bulge-disk decompositions to help identify the correct interpretation of the trends in single-Sérsic parameters. However, while multi-component models provide more detail, they require more assumptions, not least that the chosen multi-component combination is appropriate to each galaxy in question. They are also more sensitive to practical details of galaxy data, e.g. the presence of spiral arms or small, undebleded companions, and ensuring one finds the true optimal fit is considerably more difficult. The simplicity and robustness of single-Sérsic fitting means that it will long continue to be a valuable approach, especially when pushing the signal-to-noise and resolution boundaries of any dataset.

6 SUMMARY

We have studied the dependence of Sérsic index ($n$) and effective radius ($R_e$) on wavelength using a volume-limited sample of bright galaxies ($M_*, < -21.2$, $z < 0.3$), with homogeneous agriYZ JHK imaging compiled by the GAMA survey (Hill et al. 2011). The Sérsic profile parameters were obtained by exploiting the capability of galfitS-2 and galfitm to fit consistent, wavelength-dependent galaxy models to a collection of multi-wavelength imaging. These measurements have been shown to be more accurate and robust than those obtained by fitting galaxies independently in each waveband (see H13, Vika et al. 2013).

We presented the wavelength dependence of the Sérsic index and effective radius distributions for the entire sample, and for subsamples split by rest-frame ($u - r$) colour and the $r$-band Sérsic index ($n_r$). Importantly, our multi-wavelength measurements are accurate and meaningful on an individual galaxy basis. Our analysis is thus able to go a step further than previous studies and consider the wavelength variation of $n$ and $R_e$ for individual galaxies. We describe this using the ratio of the values in two wavebands, which we denote as $\langle N \rangle$ and $\langle R \rangle$, respectively. In this paper we primarily focus on variations between $g$- and $H$-band, which is representative of the behaviour for other pairs of optical and NIR bands. We present the distributions of $\langle N \rangle$ and $\langle R \rangle$ for the various colour and Sérsic index combinations, and show that their unimodality implies that results based on population trends well represent the behaviour of individual galaxies in each subsample. The dependence of median $\langle N \rangle$ and $\langle R \rangle$ on wavelength shows contrasting trends for different galaxy types, which reveal their different physical natures. The $N\langle R \rangle$ plane can be used to classify galaxies and, particularly in combination with colour and Sérsic index, identify objects with interesting properties. Finally, we have illustrated the implications of $\langle N \rangle$ and $\langle R \rangle$ on the appearance of galaxies, and demonstrated their relationship to colour gradients, by coadding images for various selections.

Our main results from all this analysis can be summarised as follows. All these results are based on a volume-limited sample of bright galaxies. The studied trends are likely to vary for the less-luminous, dwarf galaxy population, but we leave an exploration of this issue for future work.

- Galaxies of opposing colour are characterised by very different Sérsic index distributions, which depend differently upon the wavelength at which the Sérsic index is measured. The median Sérsic index for red galaxies does not depend on wavelength, while for our blue and green galaxy subsamples the median Sérsic index increases significantly at longer wavelengths. In contrast, galaxies with different colours display similar distributions of effective radius. While galaxies in our red subsample are typically slightly smaller than the others, the distributions of all colours shift consistently toward lower values at longer wavelengths.
  - Using Sérsic index to divide the galaxy population, high-$n$ galaxies display much less Sérsic index variation with wavelength than low-$n$ galaxies. Red, high-$n$ galaxies show no significant dependence of Sérsic index on wavelength at all. On average, they possess a classic de Vaucouleur profile at all wavelengths. Bluier high-$n$ galaxies show mild dependences on wavelength. However, the median Sérsic index for our green high-$n$ subsample increases toward longer wavelengths, while our more extreme blue high-$n$ subsample shows a significant decrease. The Sérsic indices of low-$n$ galaxies increase dramatically toward longer wavelengths, irrespective of colour, though our red low-$n$ subsample shows slightly less variation.
  - With regard to effective radius, low-$n$ samples of all colours display very similar behaviour. Our high-$n$ samples show stronger trends, which vary for different colour selections. In all the cases, sizes decrease toward redder wavelengths.
  - By measuring for the first time the dependence of Sérsic index on wavelength for individual galaxies ($N_r$), we find that this quantity adds important information about galaxy structure, helping to robustly separate single-component and bulge-disk systems. Low-$n$ galaxies show $N > 1$, with the value strongly increasing with the wavelength range considered, suggesting a combination of a blue exponential disk and smaller and/or higher-$n$ red spheroid. High-$n$ galaxies show rather flat trends ($N \sim 1$), indicating that they are typically one-component objects. Galaxies that deviate from these behaviours are likely to be at interesting evolutionary stages.
  - Similarly, the ratio of effective radii at different wavelengths ($\langle R \rangle$) provides insight into the structural make-up of galaxies, although it does not present such disparate behaviour for the various colour and Sérsic index subsamples. The vast majority of galaxies have $R < 1$: at longer wavelengths galaxies appear smaller. Low-$n$ galaxies show a mild dependence of effective radius on wavelength, which is identical for the different colour subsamples. High-$n$ galaxies have a more dramatic dependence, which is stronger for bluer samples.
  - Combining $N$ and $R$ together, we show that the medians of different galaxy types (in terms of colour and Sérsic index) display strikingly different variations in $\langle N \rangle$ and $\langle R \rangle$ with wavelength, which succinctly describe the correlations between their internal structures and stellar populations.
  - While galaxy subsamples do overlap in the $N\langle R \rangle$ plane, the location of a galaxy in this diagram puts useful constraints on its structural properties. This is particularly true if Sérsic index and colour are considered too, allowing one to identify, e.g., central starbursts, blue ellipticals, passive disk galaxies. The separation of galaxy populations in $N\langle R \rangle$ may improve for higher resolution and signal-to-noise imaging data.
  - On average, bright high-$n$ galaxies appear consistent with possessing multiple superimposed $n \sim 4$ components, each with different effective radii, where the larger profiles are composed of bluer stellar populations. Since the vast majority of galaxies are significantly redder in their central regions, it appears that the proposed formation of young (blue), inner stellar components in elliptical...
galaxies from accreted gas is negligible for typical bright galaxies at recent times.

ACKNOWLEDGEMENTS

This work was made possible by NPRP award 08-643-1-112 from the Qatar National Research Fund (a member of The Qatar Foundation). It was also supported by the World Premier International Research Center Initiative (WPI), MEXT, Japan. SPB gratefully acknowledges receipt of a STFC Advanced Fellowship.

GAMA is a joint European-Australasian project based around a spectroscopic campaign using the Anglo-Australian Telescope. The GAMA input catalogue is based on data taken from the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. Complementary imaging of the GAMA regions is being obtained by a number of independent survey programs including GALEX MIS, VST KiDS, VISTA VIKING, WISE, Herschel-ATLAS, GMRT and ASKAP providing UV to radio coverage. GAMA is funded by the STFC (UK), the ARC (Australia), the AAO, and the participating institutions. The GAMA website is [http://www.gama-survey.org/](http://www.gama-survey.org/).

We thank the anonymous referee for their constructive comments.

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