Resolved stellar mass maps of galaxies – I. Method and implications for global mass estimates

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ABSTRACT
We introduce a novel technique to construct spatially resolved maps of stellar mass surface density in galaxies based on optical and near-infrared (NIR) imaging. We use optical/NIR colour(s) to infer effective stellar mass-to-light ratios (M/L) at each pixel, which are then multiplied by the surface brightness to obtain the local surface stellar mass density. We build look-up tables to express M/L as a function of colour(s) by marginalizing over a Monte Carlo library of 50 000 stellar population synthesis (SPS) models by Charlot & Bruzual, which include a revised prescription for the thermally pulsing asymptotic giant branch (TP-AGB) stellar evolutionary phase. Moreover, we incorporate a wide range of possible dust extinction parameters. In order to extract reliable flux and colour information at any position in the galaxy, we perform a median adaptive smoothing of the images that preserves the highest possible spatial resolution.

As the most practical and robust, and hence fiducial method, we express the M/L in the H band as a function of (g−i) and (i−H). Stellar mass maps computed in this way have a typical accuracy of 30 per cent or less at any given pixel, determined from the scatter in the models. We compare maps obtained with our fiducial method with those derived using other combinations of bandpasses: (i) mass maps based on the M/L in NIR bands require one optical and one optical-NIR colour to avoid significant biases as a function of the local physical properties of a galaxy; (ii) maps based on M/L in i band as a function of (g−i) only are generally in excellent agreement with our best optical-NIR set, except for extremely star-forming and dust extincted regions. We further compute stellar mass maps using a model library identical to the previous one except for being based on older SPS models, which assume shorter lived TP-AGB stars. The M/L in the NIR inferred using these old models may be up to 2.5 times larger than the new ones, but this varies strongly as a function of colours and is maximal for the bluest colours.

Finally, we compare total stellar mass estimates obtained by integrating resolved mass maps with those obtained with unresolved photometry. In galaxies with evident dust lanes, unresolved estimates may miss up to 40 per cent of the total stellar mass because dusty regions are strongly under-represented in the luminous fluxes.

Key words: techniques: image processing – techniques: photometric – galaxies: fundamental parameters – galaxies: general – galaxies: photometry – galaxies: stellar content.

1 INTRODUCTION
Stellar mass may be the most fundamental parameter describing present-day galaxies. A decade ago, Gavazzi, Pierini & Boselli (1996) and Gavazzi & Scagelgio (1996) pointed out that the structure and star formation history of disc galaxies are tightly linked with stellar mass. Scogelgio et al. (2002) extended this observation to all morphologies. The advent of the Sloan Digital Sky Survey (SDSS; York et al. 2000) and improved stellar population models to estimate stellar masses, ages and metallicities have allowed to put previous claims on a more secure and detailed ground, establishing the dependence of structure, star formation and chemical enrichment histories on stellar mass (e.g. Kauffmann et al. 2003b; Tremonti et al. 2004; Gallazzi et al. 2005). More recently, van den Bosch et al. (2008) have shown that stellar mass also is the

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main parameter determining the properties of ‘satellite’ galaxies, almost irrespective of their parent dark matter halo mass or of the halo-centric distance: in other words, stellar mass is by far more crucial for predicting, or setting, galaxy properties than environment.

Bell & de Jong (2000) pointed out that the mean stellar mass density of a galaxy might be an even more basic parameter than the total stellar mass in determining the stellar populations in spiral galaxies. This conclusion has been confirmed by Kauffmann et al. (2003b) and extended to all morphological types using more than 100 000 galaxies from the SDSS. Stellar masses for most of these results were derived from spectra or colours that were averaged across much of the stellar bodies of the galaxies, arriving at a global mass-to-light (M/L) estimate.

In the light of these results, it is manifestly important to (i) test the accuracy of total stellar mass estimates and (ii) develop methods that actually map the stellar mass surface density distribution in galaxies, rather than just inferring it from single passband images rescaled by a uniform M/L. Accurate maps of stellar mass distribution of galaxies are also of fundamental importance for dynamical studies aiming at disentangling the role of secular versus environmental induced evolution (e.g. Kendall et al. 2008; Foyle et al., in preparation).

Nowadays, a wealth of multiwavelength imaging is available for large regions of the sky, covering from the ultraviolet to the optical, near-infrared (NIR) and mid-IR. While most of the multiwavelength work on galaxies has focused on modelling the total or area-averaged spectral energy distribution (SED), we propose here to combine the photometric information on a pixel-by-pixel level in order to retain the maximum spatial resolution.¹ With this method, we primarily aim at studying the stellar mass distribution within galaxies but we also aim at studying the dependence of the SED on stellar mass density.

Past work has often attempted to map stellar mass distributions within galaxies, resorting to NIR images as a proxy (e.g. Elmegreen & Elmegreen 1984; Rix & Zaritsky 1995; Seigar & James 1998; Grosbol, Patsis & Pompei 2004). More recently, Kendall et al. (2008) have studied the spiral density waves in M81 using three different methods to estimate stellar mass surface density from $K_s$-band images alone, from 0.8 μm ($I$ band) images with a pixel-by-pixel M/L correction based on $B$ – $V$ colours (Bell & de Jong 2001), and based on Spitzer 3.6 + 4.5 μm imaging.

In this work, we develop a rigorous method to derive spatially resolved stellar mass density maps, based on sets of optical/NIR images of galaxies. The basic idea is that at each position in a galaxy the surface density of stellar mass is given by

$$\Sigma_M(\alpha, \delta) = \Sigma_S(\alpha, \delta) \Upsilon_\lambda(\alpha, \delta),$$

where $\Sigma_S(\alpha, \delta)$ and $\Upsilon_\lambda(\alpha, \delta)$ are the surface brightness and the effective stellar M/L in a passband of effective wavelength $\lambda$. In turn, $\Upsilon_\lambda$ can be expressed as a function of one or more colours, as measured at the given location in the galaxy. By ‘effective’ M/L, we mean the ratio between stellar mass and the light that reaches the observer, as opposed to the light that is emitted and can possibly be absorbed by the dust inside the galaxy.² In Section 2, we derive the recipes that allow us to express M/L as a function of colours, based on a Monte Carlo library of last generation stellar population synthesis (SPS) models (i.e. the 2007 version of the models by Bruzual & Charlot 2003, hereafter BC03), which also include physically motivated prescriptions that account for dust absorption. As we will show, in order to derive M/L that are accurate within $\approx 30$ per cent, colour(s) must be accurate at 0.1 magnitude or better. This requires for each resolution element (pixel) a S/N $\gtrsim 20$. While typical imaging surveys, like the SDSS and medium-depth observation in the NIR, can easily warrant such S/N for the central and brightest pixels of a galaxy, for lower surface brightnesses ($\mu_r \gtrsim 23$ mag arcsec$^{-2}$, typically for $R \gtrsim R_e$) this condition cannot be met for individual pixels. Image smoothing allows to enhance the S/N, but at expenses of the effective image resolution. For this reason, we have developed an adaptive median smoothing code (ADAPTSMOOTH; Zibetti, in preparation) that preserves the maximum spatial information compatible with minimum S/N requirements. The image processing required to compute stellar mass maps is detailed in Section 4.

The goal of this paper is mainly to introduce this new method of stellar mass density mapping based on optical and NIR imaging. Therefore, we limit our sample to only nine galaxies, which span, however, a large range in morphologies. Our selection criteria and the sources of imaging data are presented in Section 3. Despite the small sample size, we find the very interesting result that total stellar masses estimated from resolved and from unresolved photometry differ quite significantly, as we discuss in Section 5.3. A summary with concluding remarks and an outlook of future work is given in Section 6.

2 METHODOLOGY (I): SPS MODELS

2.1 Stellar M/L from optical-NIR colours

In this section, we combine SPS models with simple prescriptions for dust attenuation to devise a set of look-up tables that allow us to estimate the effective stellar M/L, given either one or two optical/NIR colours. As mentioned above, by ‘effective’ M/L we mean the ratio between stellar mass and the light that reaches the observer, after being possibly absorbed by the dust within the galaxy. To generate our fiducial SPS models, we adopt the 2007 version of Gissel (Bruzual & Charlot 2003, CB07 hereafter), which includes revised prescriptions for the TP-AGB evolutionary phase, following Marigo & Girardi (2007) and Marigo et al. (2008).³ An accurate modelling of this phase is of particular relevance to correctly predict fluxes (hence colours and M/L) that involve the wavelength range between 1 and 2.5 μm for stellar populations of ages between 0.3 and 2 Gyr (e.g. Maraston 2005; Bruzual 2007). The emerging optical/NIR colour(s) of the stellar population at a given position in a galaxy are determined by a variety of factors, namely the star formation history (SFH), the metallicity, the amount, spatial distribution and optical properties of dust and the initial mass function (IMF) of stars. In the following, we will work under the assumption that the IMF is universal and well described by Chabrier (2003). The systematic effects on mass estimates induced by different choices

¹ Pioneering work in the pixel-by-pixel approach was already conducted by Abraham et al. (1999) and Conti et al. (2003).
² Emission lines from the gaseous interstellar medium (ISM) can affect the ‘effective’ M/L as well. We will not take their contamination into account explicitly, but only implicitly by not using passbands that include the Ha emission.³ Using simple stellar populations of different metallicities, we have compared the M/L in red and NIR bands as a function of colours predicted by CB07 and Maraston (2005) models. Although significant discrepancies up to a few tenths of a dex are seen, especially at the youngest ages, in the most relevant range of colours ($g - i > 0.2$ mag, see Section 4.2) no systematic offset is observed.
of IMF (e.g. Bell & de Jong 2001) are not of primary relevance here, as long as the IMF can be considered uniform within a galaxy. This assumption is suggested by Occam’s razor, as we lack any way of linking possible variation of IMF to local observables within a galaxy.

All other relevant parameters, SFH, metallicity, dust, are expected to vary significantly from place to place in a galaxy. To explore the effect of such differences on colours and M/L, we build a Monte Carlo library of SPS models with the following properties, as in Kong et al. (2004) and da Cunha, Charlot & Elbaz (2008). Each stellar population has a fixed metallicity, randomly chosen between 0.02 and 2 times solar, and a two-component SFH, consisting of a continuous, exponentially declining mode with random bursts superimposed. We follow Kauffmann et al. (2003a) to parametrize each SFH by a set of variables with a given prior probability distribution. The effect of dust is modelled according to the formalism introduced by Charlot & Fall (2000) to treat the differential absorption by dust in the short-lived birth clouds and in the ISM. As in da Cunha et al. (2008), the two parameters that govern dust absorption, the total effective V-band optical depth τ_V and the fraction contributed by dust in the ambient ISM μ, have 1 − tanh prior probability distributions, such that τ_V is approximately uniform over the interval from 0 to 4 and drops exponentially to zero around τ_V = 6, while μ is approximately uniform over the interval from 0 to 0.6 and drops exponentially to zero around 1. For each model, emerging fluxes and stellar masses are combined to compute colours and effective M/L.

To study how M/L in a given band depends on colours, we adopt a marginalization approach. We bin models in the one- or two-dimensional colour space we aim at studying, with a bin width \( \leq \sigma_{\text{colour}} \), the typical observational error. Specifically, we adopt a bin width of 0.05 mag in each colour dimension. Within each bin we compute the median M/L and the logarithmic rms from all parameter combinations that lead to those colours. This approach incorporates uncertainties from parameter degeneracies or model simplifications. For example, the assumption of a single metallicity in a given SPS model may be unrealistic even on local scales, but by marginalizing over a large number of random models with different metallicities we indirectly take varying metallicity into account.

In principle, more colours should provide better constrained stellar populations and hence M/L; in practice, there are limitations: most of the colour information is nearly degenerate, especially that from adjacent bands like \( r - i \) and \( i - z \). We have found that using one more colour just complicates the analysis by increasing its dimensionality without reducing the M/L uncertainty. More colours would only provide improvements if the systematic flux uncertainties in the models were smaller than 10 per cent, which current models do not reach yet. For these reasons, we limit our study to two colour indexes at most.

For practical reasons, we only consider broad passbands with extensive existing data sets: the SDSS \((u, g, r, i, z)\) and the \( J, H, K \) filters in the NIR. Among them, we discard the \( u \) band because of the typically low S/N in SDSS and the very high dust attenuation that can lead to almost complete obscuration over a significant area of a galaxy. We further discard the \( r \) band because of the strong local contamination by Hα emission in H\( \alpha \) regions: typical equivalent widths of a few hundreds Å in those regions would lead to overestimate the stellar emission by up to 0.5 mag in \( r \). Among the three NIR bands, we focus on the \( H \) as our reference band, but we note that any conclusion we present regarding this band applies almost identically to \( J \) and \( K \) as well.

It is well known from previous studies (e.g. Rix & Zaritsky 1995 appendix B, or Bell & de Jong 2001) that in NIR bands M/L variations as a function of stellar population parameters are smaller than at shorter wavelengths because the bulk of long-lived low-mass stars dominate the emission in the NIR. Moreover, dust extinction is lower at longer wavelengths. Thus, for our fiducial mass reconstruction method it is natural to choose a NIR band (namely the \( H \) band) as the ‘luminance’ band, whose surface brightness we want to convert to stellar mass surface density. As for the colour space, where we map M/L, we choose \((g - i), (i - H)\) because these colours provide the largest wavelength leverage and thus the highest sensitivity to stellar population and dust properties. This large leverage also minimizes the effect of any systematic uncertainties in the photometric calibration of SPS models or of the imaging data: 10 per cent flux uncertainties are negligible for a colour range of 2 mag, but not for a range of a few 0.1 mag. From now on, magnitudes in the SDSS bands are meant to be in the AB system, while for Johnson–Cousins filters they are expressed in Vega units. Colours that involve SDSS bands and Johnson–Cousins passbands are computed by subtracting the magnitudes in the two respective systems such that, for example \( i - H \) means \( i_{\text{AB}} - H_{\text{Vega}} \).

The top-right panel of Fig. 1 shows \( \Upsilon_H \), the M/L in \( H \) band in solar units, as a function of \((g - i), (i - H)\) colours, based on the Monte Carlo library of SPS models. Our models cover a broad sequence from blue (lower left corner) to red (upper right corner) across the colour–colour diagram, with \( \Upsilon_H \) increasing from \( 10^{-15} \) to \( 10^8 \), that is by a factor of 200. It is apparent that the \( g - i \) colour is the main predictor of the trend in \( \Upsilon_H \), which increases by 0.08 dex per 0.1 mag in \( g - i \). However, for a given \( g - i \), a range of \( \Upsilon_H \) is allowed. This is quantified in the top-left panel of Fig. 1, where we plot (solid line) the median \( \Upsilon_H \) as a function of \( g - i \) (binned in 0.05 mag). Dash–dotted lines show the maximum and minimum \( \Upsilon_H \) taken from the right-hand panel, for a given \( g - i \): the spread in \( \Upsilon_H \) is between 0.5 and 1 dex for most of \( g - i \) values, showing that the additional information from the second colour, \( i - H \), is crucial to minimize the uncertainty in \( \Upsilon_H \).

Even in the two-dimensional colour space the remaining scatter of the predicted \( \Upsilon_H \) at a given \((i - H), (g - i)\) is significant. The rms of log \( \Upsilon_H \) is represented in the colour–colour space in the bottom right-hand panel of Fig. 1. The typical rms ranges between 0.05 and 0.15 dex (i.e. between 10 and 40 per cent approximately) and is thus comparable to the effect of errors on colours of \( \approx 0.1 \) mag, except for the region occupied by ‘blue’ models \((g - i < 0.7, i - H < 2.2)\). Models in this region are characterized by relatively young stellar populations with a strongly varying NIR emission (in particular by TP-AGB stars, see also Section 2.2), which produce rms scatter up to 0.25 dex (approximately a factor of 1.8). It is interesting to see how this scatter in log \( \Upsilon_H(g - i), (i - H) \) compares with the half-range of log \( \Upsilon_H(g - i) \) that we derived from the top-right panel of Fig. 1. The latter can be considered an estimate of the typical error that one makes by replacing log \( \Upsilon_H(g - i), (i - H) \) by the median log \( \Upsilon_H(g - i) \). The bottom-left panel of Fig. 1 shows that for most \( g - i \) the mean rms scatter in log \( \Upsilon_H(g - i), (i - H) \) at any given \( g - i \) (dash–dotted line) is \( \approx 0.1 \) dex, while it is \( \approx 0.3 \) dex for log \( \Upsilon_H(g - i) \) (solid line). Through the use of two colours to determine the M/L, one can reduce the uncertainties from a factor of 2 to a factor of 1.25.

It is worth noting that the choice of prior parameter distributions in the model library can affect the estimated median M/L for a given colour (pair). The time elapsed since the beginning of star formation,
Figure 1. Effective M/L in H band as a function of colours in the Monte Carlo library based on CB07 SPS models. Top right panel: the median log $\Upsilon_H$ for models binned 0.05 $\times$ 0.05 mag$^2$ in the $(i - H) - (g - i)$ colour–colour space. Top left panel: the median log $\Upsilon_H$ for the same models binned 0.05 mag in $(g - i)$ only (solid line), and the minimum and maximum value of log $\Upsilon_H(i - H, g - i)$ along each row of the right-hand panel (dash–dotted lines). Bottom right panel: the rms of log $\Upsilon_H$ for models binned 0.05 $\times$ 0.05 mag$^2$ in the $(i - H) - (g - i)$ colour–colour space. Bottom left panel: the solid line shows the half-range of values of log $\Upsilon_H$ as a function of $g - i$ from the top right panel, compared to the mean rms of log $\Upsilon_H$ in individual colour–colour cells (dash–dotted line).

$\tau_{\text{form}}$, and the time and intensity of bursts are the parameters whose distributions affect most the median M/L because the fraction of mass hidden in old, low-luminosity stars critically depend on these parameters. As an extreme case, we test the effect of removing from our library all models with $t_{\text{form}} < 10$ Gyr. As expected, the models with larger $t_{\text{form}}$ predict larger M/L. The largest differences (from 0.1 up to 0.4 dex) are found for $g - i < 0.6$ and for the very reddest models in $i - H$ at given $g - i$. As it is shown in Section 4.2 and Fig. 6, these regions of the colour–colour space are only sparsely populated in the observations. The rest of the space is only marginally affected (typically 0.02 dex difference, increasing towards the extreme regions mentioned before). We conclude that our choice of prior is not critical when we use two colours. However, it can gain greater relevance if only one colour is used, as we show in Section 2.4. In Appendix A, we show and discuss the detailed distributions of the physical parameters that characterize the models as a function of colours. In particular, we note that extremely red colours ($g - i > 1.5$) and correspondingly very high $\Upsilon_H$ (up to 5–6) can be produced only by models with total dust optical depth $\tilde{\tau}_V \gtrsim 3$.

2.2 Comparison with models using an older TP-AGB star prescription (BC03)

Most recent works in SPS models agree on the relevance of the TP-AGB phase for a correct estimate of the NIR flux of stellar populations at ages between 0.3 and 2 Gyr (e.g. Maraston 2005; Bruzual 2007). Yet, a fully reliable quantification of this effect is still under debate. In order to illustrate the impact of different prescriptions for the TP-AGB phase (in particular, those concerning its duration), we compare M/L determinations from our standard CB07 models with those derived from the BC03 models (Bruzual & Charlot 2003), which assume much shorter lived TP-AGB stars. We have produced a library of SPS models with identical SFH, metallicity, IMF and dust properties as described before, but using the stellar evolutionary tracks and libraries of BC03.

In Fig. 2, we compare the distribution of the two model libraries in the $(i - H) - (g - i)$ colour–colour space. The intensity scale in colour shows the distribution of our default library CB07, while the distribution of BC03 models is shown by the overlaid contours. The effect of the revised TP-AGB star prescriptions in CB07 is mainly...
We have conducted the same test using the SDSS $i$−$g$−$H$ band for $-$1 to redder $i < H$. The original colour appears as an attractive alternative to on ($i$ band is fixed by the $H$ and ... systematic difference to CB07 models in this case is 0.1 dex at most, to be compared with differences of up to 0.4 dex in $H$ band (see paragraph 2.2).

In the light of these results, the use of $i$-band images for luminance and $g − i$ maps to extract $\Upsilon_i$ appears as an attractive alternative to our fiducial method, the use of $H$ band with ($g − i, i − H$) colours. While $H$ band with ($g − i, i − H$) is more accurate and stable against photometric errors because of the smaller range in $\Upsilon_H$, the use of $i$ and $g$ band is certainly cheaper in terms of observational resources and less sensitive to the still controversial modelling of TP-AGB stars. However, in Section 5, we show that the use of NIR is the only sensible way to go in two regimes: (i) in presence of heavy dust obscuration, where radiation at shorter wavelengths will not emerge, and (ii) in the case of very young stellar populations that completely dominate the optical light.

### 2.4 Comparison with Bell et al. (2003)

A one-colour method similar to the one we adopt to derive $\Upsilon_i(g − i)$ and $\Upsilon_H(g − i)$ was formerly developed by Bell & de Jong (2001) and subsequently revised by Bell et al. (2003). In appendix A2 of their paper, they give power-law fits for $M/L$ in different optical and NIR bands as a function of one optical colour. In Fig. 3 and 4, we plot the Bell et al.’s relations for $\Upsilon_H(g − i)$ and $\Upsilon_i(g − i)$, respectively, as red dotted lines, limited to the colour range actually covered in their work. We have scaled down their M/L by $-0.093$ dex to take the difference between our Chabrier IMF and their scaled Salpeter IMF (Gallazzi et al. 2008). Their M/L agree with ours only for the reddest ($g − i$) corresponding to old unextincted stellar population. Yet, the dependence on ($g − i$) is much weaker according to Bell et al.’s fits and results in large discrepancies at the blue end of the distribution, where they predict M/L approximately 10 times larger than ours. The same systematic variations occur in all bands and colours analysed in Bell et al. (2003), as can be verified using the power-law fits derived from our fiducial models which are given in Table B1 in Appendix B.

There are in fact a number of differences between our methodology and Bell et al.’s. First of all, their models are based on BC03 SPS models. However, Figs 3 and 4 show that large discrepancies are present also in comparison to our BC03-based estimates. Bell et al. (2003) do not explicitly take dust into account and, more importantly, only consider relatively smooth SFHs, starting 12 Gyr in the past and with a maximum stellar mass contribution from burst in the last 2 Gyr smaller than 10 per cent. As opposed, we do model the effect of dust up to optical depth of $\tilde{\kappa}_v \approx 6$ and, more importantly, in our library we allow young ages (of a few Gyr) and have a large fraction of star formation bursts, which are the main

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**Figure 2.** Prior distribution of models in $(i − H) − (g − i)$ colour–colour space: the colour map shows the distribution for the CB07 library, solid contours are for BC03 (1, 10 and 100 models per colour–colour bin). The effect of the revised prescription for TP-AGB stars is evident in the shift of the CB07 models to redder $i − H$ values with respect to BC03.

4 We have conducted the same test using the SDSS $z$ band instead of $i$ and obtained qualitatively identical results.

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**Table B1 in Appendix B.**
Figure 3. Comparison between CB07- and BC03-based libraries. Right-hand panel: difference of median log $\Upsilon_H$ derived using CB07 and BC03 models, binned $0.05 \times 0.05$ mag$^2$ in $(i - H) - (g - i)$. Black contours show the distribution of models in colour–colour space for CB07 (solid contours) and BC03 (dashed). CB07 models, which include longer-lived TP-AGB stars, appear to extend more to red $i - H$ than BC03, with an overall shift towards redder $i - H$ at low $g - i$, due to young stellar populations which include a significant fraction of TP-AGB. Left-hand panel: median log $\Upsilon_H$ as a function of $g - i$ for CB07- and BC03-based models, shown as solid and dashed lines, respectively. The old BC03 models with shorter-lived TP-AGB stars overestimate $\Upsilon_H$ by several tenths of dex in blue/young stellar populations, with respect to the new CB07. The red-dotted line represents the power-law fitting formula from Bell et al. (2003).

Figure 4. Effective M/L in $i$ band as a function of colours in the Monte Carlo library based on CB07 SPS models. Right-hand panel: the median log $\Upsilon_i$ for models binned $0.05 \times 0.05$ mag$^2$ in the $(i - H) - (g - i)$ colour–colour space. Left-hand panel: median log $\Upsilon_i$ for the same models binned $0.05$ mag in $(g - i)$ (solid line), and the minimum and maximum value on log $\Upsilon_i$ along each row of the right-hand panel (dash–dotted lines). Black lines represent CB07 models, while grey lines display BC03. The red-dotted line is the Bell et al.’s (2003) power-law fit.

due of our lower M/L for young stellar populations (see e.g. fig. 5 of Bell & de Jong 2001, and Section 2.1), especially when one colour only is used. On the local scales that we want to study, both dust and bursty SFHs cannot be neglected. This is easy to realize just looking at the true colour images of common spiral galaxies, where dust reddened regions are seen and young OB associations dominate in spiral arms. Therefore, we argue that our models are better suited to describe SEDs on local scales than Bell et al.’s. This may not be the case if galaxies are considered globally: in fact for ‘normal’ galaxies, global SFHs are likely to be much smoother and
3 SAMPLE AND IMAGING DATA

To test our mass map reconstruction, we select a small sample of nearby galaxies that span a broad range of morphologies and physical properties and for which a wealth of high-quality multiwavelength imaging is available. We draw our sample from the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003), a comprehensive imaging and spectroscopic study of 75 nearby galaxies ($D < 30$ Mpc) conducted in the IR with the Spitzer Space Telescope, for which coordinated observations at visible, NIR, ultraviolet and radio wavelengths are either already in place or planned. Complementing this unique data set with high-quality stellar mass maps will provide key insights into the physics of galaxies and, at the same time, will allow us to test our method in the best characterized physical conditions. Among the 75 SINGS galaxies, we select nine for which SDSS and medium/deep NIR (1–2.5 μm) imaging is available. The latter is taken either from GOLD Mine (Gavazzi et al. 2003), a large data base that provides NIR images of 1568 galaxies (mainly in the Virgo cluster and the Coma super-cluster), or from the third data release of UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007, Warren et al., in preparation), that uses the United Kingdom Infrared Telescope (UKIRT) Wide Field Camera (WFCAM; Casali et al. 2007).

The nine galaxies are listed in Table 1 with their NGC name (Column 1), coordinates (Columns 2 and 3) and morphological type (Column 4) according to the RC3 catalogue (de Vaucouleurs et al. 1991). Distances are reported in Column 5. Seven out of the nine galaxies belong to the Virgo cluster and, following Gavazzi et al. (1999), we assign them at a distance of 17.1 Mpc. For the other two galaxies, we use distances as given by NED based on their measured redshift, assuming $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. Based on the computed distance and the pixel scale of the different NIR cameras we compute also the angular scale (Column 6) and pixel scale (Column 7): for the median seeing of $\sim 1.4$ arcsec, we could resolve physical scales of $\sim 120$ pc in all cases, although the pixel scales range from 18 to 132 pc. We use $H$ as NIR band except for NGC 4569, for which only $K_s$ is available. Our sample includes one elliptical galaxy, two early type Sab spirals, one Sb, four Sbc’s (including one peculiar) and one Sc, thus spanning the whole range of morphologies for ‘normal’ (i.e. not irregular) galaxies.

True colour images of the galaxies sorted by morphological type are presented in Fig. 5. The NIR band is mapped in the red channel, $i$ band in the green and $g$ in the blue; the three channels are shown in logarithmic intensity scaling and are balanced to show a solar SED as white. The images that we show in Fig. 5 are matched, calibrated and filtered as explained in Section 4. Each panel reports the physical scale in kpc and a rod whose length corresponds to 50 pixel.

3.1 Image reduction and calibration

Imaging data for this study are taken from three different sources, each requiring slightly different pre-reductions and calibrations, that we describe in this section.

For the optical images ($g$, $i$ and $z$ bands), we completely rely on the seventh data release of the SDSS (York et al. 2000; Abazajian et al. 2009). SDSS images come in the format of ‘corrected frames’, that are bias-subtracted, flat-fielded cuts of long imaging scans. Given the relatively large size of our galaxies, in some cases two different scans must be combined. In the general case, we reduce each scan separately: first we join the frames, then we compute an accurate astrometric solution using stars from the SDSS catalogue. We subtract the sky background by fitting a plane surface to the pixels in a series of boxes that we define around the galaxy, with a typical size of roughly one tenth of the galaxy. The fitted plane is allowed to be tilted in the scan direction only, in order to take temporal background variations into account. The rms of the median background levels among the boxes provides an estimate of the large scale background fluctuations that is used later on to make S/N cuts. If more than one scan is used, we choose a primary scan (where most of the galaxy is contained) and we rescale all secondary scans that all of the GOLD Mine images used in this work have pixel scales

| Denomination | RA (J2000.0) | Dec. (J2000.0) | Morph. type | Distance (Mpc) | Angular scale (pc arcsec$^{-1}$) | Pixel scale (pc pixel$^{-1}$) | NIR | NIR source |
|--------------|-------------|---------------|-------------|----------------|---------------------------------|-------------------------------|-----|------------|
| NGC 3521     | 11°05′48″6″ | −00°6′02″09″  | SABb        | 9.2            | 45                              | 18                            | $H$ | UKIDSS     |
| NGC 4254     | 12°18′49″6″ | +14°24′59″    | SaC         | 17.1           | 82                              | 132                           | $H$ | GOLD Mine  |
| NGC 4321     | 12°22′54″9″ | +15°4′29″1″   | SABbc       | 17.1           | 82                              | 132                           | $H$ | GOLD Mine  |
| NGC 4450     | 12°28′29″6″ | +17°3′05″06″  | SaAb         | 17.1           | 82                              | 124                           | $H$ | GOLD Mine  |
| NGC 4536     | 12°34′27″0″ | +02°11′17″    | SABbc        | 17.1           | 82                              | 132                           | $H$ | GOLD Mine  |
| NGC 4552     | 12°35′39″8″ | +12°33′23″    | E            | 17.1           | 82                              | 33                            | $H$ | UKIDSS      |
| NGC 4569     | 12°36′49″8″ | +13°5′09′46″ | SABb         | 17.1           | 82                              | 132                           | $K_s$ | GOLD Mine |
| NGC 4579     | 12°37′43″5″ | +11°4′09′05″  | SABb         | 17.1           | 82                              | 132                           | $H$ | GOLD Mine  |
| NGC 5713     | 14°40′11″5″ | −00°2′17′20″  | SABbc        | 25.9           | 126                             | 51                            | $H$ | UKIDSS      |
between 1.5 and 1.6 arcsec pixel$^{-1}$, that severely undersample the point spread function (PSF). This does not represent a problem for the following analysis though, as a sufficient physical resolution is provided anyway (Table 1).

For UKIDSS images, we have used stacks from the third data release, which is described in detail in Warren et al. (in preparation). The pipeline processing and science archive are described in Irwin et al. (in preparation) and Hambly et al. (2008). Sky subtraction and astrometric calibrations are performed exactly as for GOLD Mine images. The UKIDSS photometric system is described in Hewett et al. (2006), and the calibration is described in Hodgkin et al. (2009). The absolute photometric accuracy is typically around few 0.01 mag. We note that the pixel scale of 0.4 arcsec pixel$^{-1}$ perfectly matches SDSS images.

In both GOLD Mine and UKIDSS data sets, the typical depth reached by the NIR images used in this study is $\mu_H \approx 20.5$ mag arcsec$^{-2}$ ($3\sigma$ on an arcsec$^2$).

All fluxes are corrected for Galactic foreground extinction, as given in NED or the SDSS data base, which are based on Schlegel, Finkbeiner & Davis (1998).

## 4 METHODOLOGY (II): FROM MULTIBAND IMAGES TO MASS MAPS

### 4.1 Image processing

Images in different bands must be registered and resampled to a common resolution before pixel-by-pixel colour information can
be extracted. To do this, we use \texttt{SWARP} and the astrometric solutions computed in the previous section. We choose to degrade all sky-subtracted images to the lowest resolution image for each galaxy. In practice, for all images taken from GOLD Mine this translates into degrading the SDSS images to the NIR pixel scale,\(^7\) while the original pixel scale is kept for the UKIDSS data. In principle, images taken with different instruments, in different bands and seeing conditions must also be convolved to a common PSF. However, we do not apply such convolution, as the PSFs are already similar and a convolution would corrupt the noise properties.

As shown in Section 2, colours must be accurate at better to \(\lesssim 0.1\) mag to compute M/L that match theoretical uncertainties. In turn, this requires surface brightness in each band to be accurate within \(\approx 0.05\) mag or S/N \(\gtrsim 20\) per pixel. The noise budget includes local photon noise, assumed to be Gaussian, and background fluctuations that may become the dominant source of uncertainty at low surface brightness.

Local photon noise can be reduced to the required level with low-pass filters, using a smoothing kernel of sufficiently large size. However, a fixed-width kernel produces a uniform degradation of the effective spatial resolution of the entire image, including bright regions of the galaxy where no or minimal smoothing is required. For this reason, we have implemented a new code to perform image smoothing with a variable kernel, whose size is adapted to the local S/N. This code is called \texttt{ADAPTSMOOTH} and will be presented in detail in a forthcoming paper (Zibetti, in preparation). Briefly, the idea is to replace the intensity in each pixel with the median of pixels in a circle of radius \(R\) of surrounding pixels, where \(R\) is determined as the minimum radius required to attain the minimum S/N of 20. The procedure works by increasing \(R\) iteratively. If the minimum S/N of 20 cannot be reached even with the maximum smoothing radius \(R_{\text{max}}\), the pixel is flagged and assigned a value of 0. In this work, we adopt \(R_{\text{max}} = 13\) pixels for the GOLD Mine images (corresponding to 20 arcsec) and 20 for the UKIDSS images (corresponding to 8 arcsec). In this way, the full spatial resolution is preserved in the brightest regions of a galaxy, while increasingly strong smoothing is applied to lower and lower surface brightness regions.

\texttt{ADAPTSMOOTH} is run a first time on the individual images in each band. A mask that contains the smoothing radius for each pixel (or an overflow value where the required S/N cannot be reached within \(R_{\text{max}}\)) is the output for each image. In order to match the spatial resolution between all three bands, we combine the masks into a common mask with the maximum of the three smoothing radii at a given position. We then apply an intensity cut to take into account large-scale background fluctuations, as computed from the sky box statistics. All pixels with an intensity in the smoothed image less than 10 times the large-scale background fluctuation rms in one of the three bands are flagged with the overflow value in the mask. Furthermore, we manually edit the mask to flag stars and other interlopers. With this mask, we re-run \texttt{ADAPTSMOOTH} in all bands in ‘input mask’ mode, that is using the smoothing radii as given in the input mask. In pixels where the overflow value is set, a default value for undefined is output. The adaptively smoothed images that result from this procedure are shown in the three-colour composite images of Fig. 5. We note that (i) the NIR images put the strictest constraints for smoothing and intensity cuts; (ii) the intensity cut we adopt here is less strict than required to ensure S/N \(\gtrsim 20\) at all positions and can produce systematic colour offsets. However, the intensity threshold in the NIR in all cases is so high that background fluctuations in the optical are negligible in the regions that make it through the cut. Effectively, the intensity cut ensure that the error on colour due to background fluctuations is roughly the same as the error on the \(H\) band only, that is 10 per cent at most.

From the adaptively smoothed and matched images in the three (or two) bands we compute colours and surface brightness in solar units per pc\(^2\) (in the ‘luminance’ band), for each pixel. From colours, we derive the M/L as explained in Section 2 and can multiply it by the surface brightness in order to obtain the stellar mass surface density.

### 4.2 Models and observations in the colour–colour space

Before illustrating the results of our stellar mass map reconstruction method, we check to which extent the models can actually reproduce the observed pixel-by-pixel colours in galaxies. In Fig. 6, we plot the distribution of pixels in the \((g - i, i - H[K_s])\) space for the nine galaxies in our sample. The relative number density of pixels per colour cell is displayed according to the colour key on the right-hand side. On the top of it, we overlay contours showing the number density of models in our library. We observe that the vast majority of pixels in our galaxies lie within the contours that trace the distribution of models. Although this is \textit{not} a proof that models are correct, it reassures us that we can reproduce the observations. On the other hand, a comparison with Fig. A1 shows that broad ranges in all physical parameters are required for the models to match the observed colours.

Few pixels have colours not covered by models, in NGC 4552, 3521 and 5713. Their M/L must be derived via extrapolation (minimum surface curvature fitting). We have scrutinized these pixels that lie blue-ward of the model contours \((i - H)\) and found that they are from the lowest surface brightness regions. A possible explanation for this could be just the influence of background fluctuations in the NIR, that can certainly account for errors of \(\approx 0.1\) mag. Further, in NGC 4552 the data show at face-value a strong \(i - H\) colour gradient, with bluer values at larger radii, which does not correspond to any similar trend in \(g - i\). A non-uniform background cannot explain this effect, since the strength of this gradient appears the same at different position angles. A metallicity gradient can also be invoked, but not as a full explanation, since we do have low-metallicity models in our library and yet we are unable to recover such blue \(i - H\). Michard (2002) and Wu et al. (2005) have pointed out in the past that optical thinned CCDs can have very extended PSF wings (especially in \(i\) band), up to arcmin scales. Such wings are not expected in the NIR, although no studies of the phenomenon have been conducted so far. We can speculate that large-angle PSF wings from scattering in \(i\) (and \(g\), but not in \(H\)) band cause the ‘blue’ \(i - H\) halo around NGC 4552 (and possibly the blue ‘halo’ around NGC 3521 and 5713). Indeed, we observed the very same effect also in another elliptical of similar apparent size and luminosity, NGC 4621 (which is not in the current sample).

Despite those possible systematics at low surface brightness levels, Fig. 6 suggests that our method is on a solid footing for regions within the classically defined optical radius of a galaxy.

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\(^{7}\) In order to correctly propagate the noise properties of the images while degrading the resolution it is important to run \texttt{SWARP} with an oversampling factor equal to the ratio between the final and the original pixel scale.
5 RESULTS

5.1 M/L and mass maps

In Fig. 7, we show the resulting M/L maps ($H[K_s]$ band) for the nine galaxies, with light (dark) tints representing low (high) M/L, as indicated in the side colour key. Early type galaxies tend to have uniform M/L, due to their phase-mixed stellar populations and lack of substantial dust obscuration. In later type galaxies, blue stellar populations in the spiral arms result in a spiral structure of lower M/L. For the two grand-design spirals (NGC 4321 and 4254), the radial decrease of M/L is a clear effect of the younger, lower metallicity stars that populate the outer disc (see e.g. Portinari & Salucci 2009). The presence of an old/metal rich bulge is at the origin of the high-M/L regions in the inner parts of most spirals, except NGC 5713 which has a peculiar morphology. Dust lanes, which are observable in the true colour images of Fig. 5 as reddish intrusions, are highlighted in the M/L maps by the most extreme high values, as one expects as a consequence of light absorption.

The stellar mass maps, resulting from multiplying $H[K_s]$-band intensity with the M/L of Fig. 7, are shown in Fig. 8. What is most striking here is the overall smoothness of the stellar mass distribution across the entire morphological sequence. The prominent spiral arms which are seen in the true colour images (and in the individual bands) are greatly reduced in the mass maps. We will quantitatively analyse the relative bias of galaxy structure in mass maps versus brightness maps at different wavelength in paper II of this series.

To give a more quantitative idea of how structure changes from a light weighted to a mass weighted view, we note that the relative arm-interarm contrast for NGC 4321 decreases roughly by a factor 2 when we measure it from the mass map rather than from $i$- or $H$-band images.

5.2 Comparison between different methods

We now compare the stellar mass maps obtained with the different methods described in paragraph 2. We consider (a) our fiducial method based on $\Upsilon_H(i-H, g-i)$ as derived from CB07 SPS models, in conjunction with $H$-band images; (b) $\Upsilon_H(i-H, g-i)$ from BC03 SPS models, with $H$-band images; (c) $\Upsilon_H(g-i)$ from CB07 SPS models, with $H$-band images; (d) $\Upsilon_H(g-i)$ from BC07 SPS models, in conjunction with the $i$-band images. In particular, we present such comparisons for NGC 4321, which is representative of normal galaxies with minor dusty regions and moderate star formation activity, and for NGC 5713, which is the extreme case in terms of dusty and intensely star-forming regions. Mass maps comparisons for NGC 4321 and 5713 are presented in Figs 9 and 10, respectively. In both figures, the top left-hand panel shows the stellar mass map obtained with the fiducial method (a). The other three panels display the logarithmic difference between the mass maps obtained with methods (b)–(d), respectively, and

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8 Note the bright nucleus in NGC 4552: the low-ionization nuclear emission-line region (LINER) shines in blue $g-i$ colour that is ‘interpreted’ by our algorithm as young stellar populations. The nuclear pixels can also be seen as a track directed towards the lower-right corner in Fig. 6.
that from the fiducial method (a). For NGC 4321, we observe that the four methods result in very similar structure, with rms in the residuals between 5 and 7 per cent. Method (d) ($\Upsilon_g$ from CB07) provides the closest match to the default method (a), with an average pixel-by-pixel offset of 3 per cent and residual rms of 5 per cent. Using $g-i$ alone to constrain M/L in $H$ band results in worse agreement with method (a) (rms = 7 per cent). This is expected from Figs 1 and 4: while $\Upsilon_g$ shows little dependence on $i-H$, on the contrary $\Upsilon_H$ does significantly depend on both colours. As for the difference between using CB07 or BC03 (method a and b), we note a systematic offset of approximately +0.1 dex going from CB07 to BC03, although the difference map looks very uniform.

Contrary to the ‘normal’ galaxy NGC 4321, NGC 5713 is characterized by intensely star-forming regions and prominent dust lanes. Models based on CB07 and BC03 predict very different M/L especially in presence of very young stellar populations (see Fig. 3), as shown in the top-right panel of Fig. 10. All blue regions (cf. Fig. 5) have masses over-estimated by up to 0.4 dex (2.5 times) in BC03 models. A qualitatively similar (but quantitatively smaller, up to 0.25 dex only) overestimate of the mass of regions dominated by young stellar populations arises from method (d): in this case the median $\Upsilon_f(g-i)$ is not the representative for these extreme stellar populations that lie to the leftmost edge of the model colour distribution (see Fig. 6). This appears to be the case also for method (c) and demonstrates the need for a second colour to properly describe this region of the parameter space.

We further explore the relative bias of different stellar mass estimation methods in Fig. 11. We consider the total stellar mass of galaxies as given by the integral of the resolved maps and plot the logarithmic difference with respect to our reference method (a). In addition to the four methods discussed above, we show the relative bias for other three methods: $\Upsilon_g$ based on BC03 models, $\Upsilon_H(g-i)$ and $\Upsilon_f(g-i)$ based on Bell et al. (2003) fitting formulae. Galaxies are sorted in morphological type, from E to the left-hand side to Sc to the right-hand side, and different symbols refer to different methods, according to the figure legend. We observe that total mass estimates from $\Upsilon_f(g-i)$ (CB07) is in excellent agreement with our fiducial method $\Upsilon_H(g-i)$ (CB07): absolute deviations are $<0.03$ dex for all galaxies ($0.012$ dex on average) and no bias is seen ($\langle \Delta \log M_* \rangle = -0.004$ dex). As already noted on the resolved maps of Figs 9 and 10, using the optical $g-i$ colour index alone to constrain M/L in NIR bands provides instead a very poor match to the results of the 2-colour method: mass estimates are biased low by approximately 0.1 dex for most galaxies and a substantial scatter is seen.

Mass estimates based on BC03 models give systematically higher values with respect to CB07: this is not surprising given the lower M/L in CB07 due to the new TP-AGB prescription and is consistent with fig. 8 of Cimatti et al. (2008). However, by comparing stellar mass estimates based on BC03 model predictions, we note that those based on $H$ band are systematically higher than those based on $i$ band, as opposed to the absence of bias observed with CB07 models. This might be an indication that the role of TP-AGB stars in BC03 models is underestimated: in fact, the emission of these stars is relatively more intense in $H$ than in $i$ band; hence, by underestimating their contribution one would

![Stellar mass maps](image_url)
conversely overestimate M/L by a larger amount in $H$ than in $i$ band.

Mass estimates based on the fitting formulae of Bell et al. (2003) are substantially higher than all mass estimates based on our models, as expected from Figs 3 and 4. In particular, using these fitting formulae, we grossly overestimate the stellar masses of blue star-forming galaxies, up to by a factor of 2.5. We stress that the difference cannot be due to the new TP-AGB prescription alone: the Bell et al. (2003) formulae rely on BC03 SPS models, yet they overestimate stellar masses even relative to our BC03-based methods. As discussed in Section 2, the main reason why our estimates differ from Bell et al.’s is the different prior distribution of SFHs, particularly concerning the age and the relative importance of bursts. Despite the smaller dynamical range of M/L in Bell et al.’s models, mass estimates derived from their prescription based on $i$ and $H$ band, respectively, are in reasonable agreement only for 6/9 galaxies; in the other three cases, they disagree by approximately 0.15 dex (40 per cent). This indicates that Bell et al.’s fitting formulae have, in general, a poor internal consistency if applied pixel by pixel.

### 5.3 Mass estimates from colour maps versus global colours

In this section, we investigate the difference in determining the total stellar mass of a galaxy by integrating resolved stellar mass maps, like those presented in the previous sections, and by using global fluxes and colours to estimate M/L, as is usually done. More specifically, we are going to compare

\[
M_{\text{resolved}} = \sum_j f_{H,j} \Upsilon_H [(g - i)_j, (i - H)_j]
\]

against

\[
M_{\text{unresolved}} = \Upsilon_H [(g - i)_{\text{global}}, (i - H)_{\text{global}}] \sum_j f_{H,j},
\]

where $f_H$ is the $H$-band surface brightness and the index $j$ denotes quantities for individual pixels. We call $Q$ the ratio $M_{\text{unresolved}} / M_{\text{resolved}}$ and report this number for each galaxy in the nine panels of Fig. 12. For four of nine galaxies, the ratio $Q$ is close to 1 within a few per cent, but for the others $Q < 0.9$ down to 0.6. This indicates that the same mass estimator drawing on global colours misses 40 per cent of the mass measured in a resolved map. The source of this difference is illustrated by the histograms of Fig. 12 and ultimately can be traced to the strong non-linearity of the relation between colour(s) and M/L. For each galaxy, all pixels are binned according to their estimated local $\Upsilon_H$. The grey-shaded histogram represents the mass in each bin as computed from the local flux and $\Upsilon_H$. The empty histogram shows the mass contributed by each bin if $\Upsilon_H$ from total fluxes (marked by the vertical dot–dashed line) were adopted. As obvious, the grey histogram is above the empty histogram for all bins where $\Upsilon_H$ is larger than the global value and, conversely, it is below for bins where $\Upsilon_H$ is smaller. The area below the grey histogram gives the stellar mass estimate from resolved mass maps, while the area below the empty histogram gives the mass based on global colours. For narrow $\Upsilon_H$ distributions, the difference between the pixels where the global M/L overestimates the mass and those where it underestimates it almost balances: this is
Figure 9. Comparison between stellar mass maps obtained with different methods/models for NGC 4321 (M100). Top left panel is the map obtained with our fiducial model CB07 using two colours $(i - H), (g - i)$ to extract M/L in $H$ band. The other three panels show the logarithmic difference between three alternative methods and the fiducial one. In the top right panel, we use the same method applied to BC03 models. In the bottom left panel, we use CB07 again, but $\Upsilon_H$ is derived from $g - i$ alone (see Fig. 1, top left panel). Finally, in the bottom right panel, M/L is determined in $i$ band from $g - i$ alone (see Fig. 4 left-hand panel) from CB07 models.

Figure 10. Same as Fig. 9 but for NGC 5713.
the case for NGC 4552, 4450, 4579 and 4321, that all have \(Q > 0.9\). For broader distributions in \(\Upsilon_H\), we observe two facts: (i) the global M/L is lower than the mean of the distribution because low-\(\Upsilon_H\) regions dominate the flux and hence the colours of the galaxy; (ii) the extended high \(\Upsilon_H\) wing is exponentially amplified in the grey histogram with respect to the empty one. As a result, galaxies with a broad M/L distribution have large differences between resolved and unresolved mass estimates, up to approximately 40 per cent. 

As we can see comparing Figs 12 and 5, this is especially the case for galaxies with substantive dust-obscured regions (i.e. NGC 4569, 4536, 3521 and 5713). Dust obscured regions, in fact, contribute a fraction of the flux and influence the global colours only marginally, although they may conceal a significant amount of stellar mass. In our most extreme case, NGC 4536, regions with \(\Upsilon_H > 1\) contribute only roughly 7 per cent of the total H-band luminosity, but around 20 per cent of the stellar mass. Such a low impact in terms of luminosity also implies that these dust obscured regions can affect the global colours at a level of \(\approx 0.1\) mag at most, such that it is observationally impossible to correctly weight them using unresolved photometry.

In Fig. 13, we analyse the difference between unresolved and resolved total stellar mass estimates for different methods, as indicated in the legend. We plot the logarithmic difference between unresolved and resolved total stellar mass estimates (i.e. log \(Q\)) both obtained with the same method. The dustiest and most irregular galaxies (namely, NGC 4569, 4536, 3521 and 5713) display the largest differences. They appear enhanced in two-colour based methods, most likely because these methods can better disentangle between dust and other stellar population parameters. For the other five more regular galaxies a clear trend is observable for all methods: the differences between resolved and unresolved stellar mass estimates increase going from early to late types. This is just a consequence of mass differences being larger for larger pixel colour spread and of colour spread being larger in later type galaxies (i.e. of early type galaxies being more uniform).

The dynamical range of models in M/L determines the relative amplitude of the unresolved estimate bias. For a given model library and method (one or two colours), this is generally smaller in the NIR than in I band. The bias is also smaller using Bell et al.’s fitting formulae, which have a much smaller M/L dynamical range with respect to our model libraries. 

In Section 2.4, we argued that our model libraries are better suited to describe local scales in terms of SFH and dust attenuation with respect to the Bell et al. (2003) fitting formulae. However, we left the question open whether Bell et al. (2003) might provide better fits to the SED of galaxies as a whole, as they are less biased towards star formation bursts. If this is the case, we must expect Bell et al.’s stellar mass estimates based on unresolved photometry to agree with our own estimates from resolved maps better than our estimates based on unresolved photometry do. In order to make this comparison fair in terms of SPS models, we confront the estimates based on Bell et al.’s formulae with our BC03-based ones. We find that mass estimates based on Bell et al.’s \(\Upsilon_H(i-g)\) and unresolved photometry are on average 0.12 dex larger than estimates done by integrating mass maps based on BC03 \(\Upsilon_H(i-H, g-i)\) (rms 0.1 dex), whereas masses derived with BC03 \(\Upsilon_H(i-H, g-i)\) drawing on unresolved photometry are smaller by 0.08 dex on an average (rms 0.06 dex). This shows that even with unresolved photometry (and assuming the same SPS models) Bell et al.’s (2003) fitting formulae do not perform better than our look-up tables do. 

6 SUMMARY AND CONCLUDING REMARKS 

In this paper, we have developed a method that is capable of reconstructing resolved stellar mass maps of galaxies from multiband optical/NIR imaging, with typical statistical uncertainties of 0.1 – 0.15 dex on local scales. We have realized a Monte Carlo spectral library of synthetic stellar populations based on the 2007 version of Bruzual & Charlot (2003) code (CB07), which includes a new prescription to treat the TP-AGB stellar evolutionary phase according to the latest isochrones by Marigo & Girardi (2007) and Marigo et al. (2008). Prescriptions to treat dust à la Charlot & Fall (2000) are also incorporated. By marginalizing over all other parameters we obtain look-up tables that contain median estimates of M/L in different bands as a function of one or two optical/NIR colours.

From practical and theoretical considerations, we arrive at \(g, i, H[K]_i\) as a good set of bandpasses and express \(\Sigma_{M*} = \Sigma_{g, i, H[K]}(g - i, i - H)\); this combination allows to carefully take young stellar populations and dust obscuration into account, while avoiding strong Hα contamination in \(H\alpha\) regions. We demonstrated that the use of a second colour is required to determine \(\Upsilon_H\) with uncertainties as low as 0.1 – 0.15 dex. Combining \(g\) and \(i\) bands alone, \(\Sigma_{M*} = \Sigma_{g, i}(g - i)\), provides a good approximation to our best method based on \(g, i, H\) for ‘normal’, close to face-on galaxies. However, it may give highly biased results in presence of very young stellar populations or severe dust extinction, where the \(i\)-band flux (7000 Å) is much more subdominant, in the first case, or more attenuated than in NIR (1–2 μm), in the second case.

On the other hand, the flux in the NIR bands appears more sensitive to the still debated role of TP-AGB stars: old models with shorter-lived TP-AGB stars overestimate M/L in \(H\) band by \(\approx 0.1\) dex (even up to 0.4 dex for young, unextincted stellar populations) with respect to the current models.

It must be stressed that we account for dust only through its \(\pi\)-averaged extinction (see Charlot & Fall 2000). Although this assumption is generally reasonable, there are cases where it fails, such as NGC 3521 (Fig. 5): it is immediate to see that the far part...
of the dusty disc (on the east side) reflects back the light of the bright inner regions of the small bulge and the disc. This results in the artificial asymmetry of the reconstructed mass map of Fig. 8. This kind of artefacts is unavoidable unless a very careful three-dimensional radiative transfer modelling is performed, which is well beyond the scope of the present mass reconstruction method.

We have applied our modelling to a small pilot sample of nearby galaxies, creating pixel-by-pixel maps of the stellar surface mass density. In general, these maps look quite smooth (Fig. 8), and hence dynamically plausible, with the prominent spiral arms of young stars and dust greatly reduced. Detailed comparisons with estimates of dynamical disc masses via vertical kinematics will enable us to accurately quantify systematics in our method. We note that preliminary results\(^9\) from the Disc Mass survey (Verheijen et al. 2007) appear in good agreement with the M/L inferred in this work, which are significantly lower than those derived using the prescriptions of Bell et al. (2003).

Our analysis highlights an important bias in total stellar mass estimates when spatially unresolved photometric measurements and colours are used: the stellar mass contribution of dust obscured regions to the total is severely underestimated from unresolved photometry, as those regions contribute very little flux and negligibly affect colours. Mass estimates based on global fluxes can be biased low by up to 40 per cent. The present sample is too small to draw conclusions on the consequences that this effect may have for galaxy stellar mass functions, but we can envisage that resolved mass estimates may steepen the faint-end slope of the stellar mass functions as estimated so far. We will address this issue with a larger and more representative sample in a forthcoming paper of this series.

After having put the foundations to obtain stellar mass maps in this paper, in the following papers of this series, we will address questions like: how do structural parameters change going from light to stellar mass? How can we quantify the bias in unresolved stellar mass estimates as a function of other observational

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\(^9\) M. Bershady’s communication in ‘Unveiling the mass’ workshop, Queen’s University, Kingston, Canada, 15–19 June, 2009.
parameters? How do SED properties depend on local stellar mass surface density? Can the inclusion of constraints from longer wavelength improve our mass reconstruction method?

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APPENDIX A: MODEL PHYSICAL PARAMETERS IN THE OPTICAL-NIR TWO-COLOUR SPACE

In this appendix, we illustrate how distributed the models of our Monte Carlo SPS library are in the \((g - i) - (i - H)\) colour space in terms of input physical properties. We consider: the total effective optical depth of the dust in \(V\) band, \(\hat{\tau}_V\); the metallicity, \(Z\); the inverse exponential time scale of star formation, \(\gamma\); the time of formation of the first stars, \(t_{\text{form}}\) (taken as look-back time). Similarly to Fig. 1, each of the four main panels of Fig. A1 shows the median value of an input parameter for all models that end up in a given colour–colour bin. The insets show the corresponding rms. We can easily distinguish two main regimes: blue models with \(g - i \lesssim 1\) and \(i - H \lesssim 2.3\), and all the rest. Blue models have the lowest \(\hat{\tau}_V\) and \(\gamma \lesssim 0.4 \text{ Gyr}^{-1}\) corresponding to star-formation time scales longer than 2.5 Gyr, without any obvious dependence on colours and with a uniform large scatter. As opposed, the models in the blue regime span the whole range of \(t_{\text{form}}\) and metallicity, with an orthogonal systematic dependence on colours: older \(t_{\text{form}}\) correspond to redder \(g - i\) irrespective of \(i - H\), while higher metallicities correspond to redder \(i - H\), almost independent on \(g - i\). In the rest of the colour–colour space the change in colours appears to be largely driven by the dust, with the other three parameters being decisive only to determine the most extreme colours (i.e. at the edges of the distribution).

APPENDIX B: POWER-LAW FITS TO M/L AS A FUNCTION OF ONE COLOUR

In Table B1, we report the parameters of power-law fits to the M/L in different bandpasses as a function of one optical colour,

\[
\log \Upsilon_\lambda(\text{colour}) = a_\lambda + (b_\lambda \times \text{colour}).
\]

This table is meant to provide a direct comparison with table 7 of Bell et al. (2003). Power-law fits to the M/L of our CB07-based models are estimated by the following robust method: in first place models are binned in colour in intervals of 0.05 mag; for each bin the median M/L is computed and finally the power-law fit is computed.

Figure A1. The median value of the input physical parameters of our library models as a function of \((g - i) - (i - H)\). The insets show the rms of the parameter values in each colour–colour bin. Panel (a): the total effective optical depth of the dust in \(V\) band, \(\hat{\tau}_V\); (b): the stellar metallicity, \(Z\); (c): the inverse exponential time scale of the continuous component of the SFH, \(\gamma\); (d): the time elapsed since the beginning of the SFH, \(t_{\text{form}}\).
Table B1. Power-law fitting parameters for $\log \Upsilon_\lambda$(colour) = $a_\lambda + (b_\lambda \times \text{colour})$.

| Colour | $a_g$ | $b_g$ | $a_r$ | $b_r$ | $a_i$ | $b_i$ | $a_z$ | $b_z$ | $a_J$ | $b_J$ | $a_H$ | $b_H$ | $a_K$ | $b_K$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $u - g$ | -1.628 | 1.360 | -1.319 | 1.093 | -1.277 | 0.980 | -1.315 | 0.913 | -1.350 | 0.804 | -1.467 | 0.750 | -1.578 | 0.739 |
| $u - r$ | -1.427 | 0.835 | -1.157 | 0.672 | -1.130 | 0.602 | -1.181 | 0.561 | -1.235 | 0.495 | -1.361 | 0.463 | -1.471 | 0.455 |
| $u - i$ | -1.468 | 0.716 | -1.193 | 0.577 | -1.160 | 0.517 | -1.206 | 0.481 | -1.256 | 0.422 | -1.374 | 0.393 | -1.477 | 0.384 |
| $u - z$ | -1.559 | 0.658 | -1.268 | 0.531 | -1.225 | 0.474 | -1.260 | 0.439 | -1.297 | 0.383 | -1.407 | 0.355 | -1.501 | 0.344 |
| $g - r$ | -1.030 | 2.053 | -0.840 | 1.654 | -0.845 | 1.481 | -0.914 | 1.382 | -1.007 | 1.225 | -1.147 | 1.144 | -1.257 | 1.119 |
| $g - i$ | -1.197 | 1.431 | -0.977 | 1.157 | -0.963 | 1.032 | -1.019 | 0.955 | -1.098 | 0.844 | -1.222 | 0.780 | -1.321 | 0.754 |
| $g - z$ | -1.370 | 1.190 | -1.122 | 0.965 | -1.089 | 0.858 | -1.129 | 0.791 | -1.183 | 0.689 | -1.291 | 0.632 | -1.379 | 0.604 |
| $r - i$ | -1.405 | 4.280 | -1.155 | 3.482 | -1.114 | 3.087 | -1.145 | 2.828 | -1.199 | 2.467 | -1.296 | 2.234 | -1.371 | 2.109 |
| $r - z$ | -1.576 | 2.490 | -1.298 | 2.032 | -1.238 | 1.797 | -1.250 | 1.635 | -1.271 | 1.398 | -1.347 | 1.247 | -1.405 | 1.157 |
| Colour | $a_B$ | $b_B$ | $a_V$ | $b_V$ | $a_R$ | $b_R$ | $a_I$ | $b_I$ | $a_J$ | $b_J$ | $a_H$ | $b_H$ | $a_K$ | $b_K$ |
| $B - V$ | -1.330 | 2.237 | -1.075 | 1.837 | -0.989 | 1.620 | -1.003 | 1.475 | -1.135 | 1.267 | -1.274 | 1.190 | -1.390 | 1.176 |
| $B - R$ | -1.614 | 1.466 | -1.314 | 1.208 | -1.200 | 1.066 | -1.192 | 0.967 | -1.289 | 0.822 | -1.410 | 0.768 | -1.513 | 0.750 |

via weighted linear least squares, where the number of models in each bin is adopted as weight. Magnitudes in the SDSS bands are meant to be in the AB systems, while for Johnson–Cousins filters they are expressed in Vega units.

As already discussed in the text, the slopes of our relations are significantly steeper than those computed by Bell et al. (2003) mainly because of the different assumptions about the SFH, in terms of ages and bursts. For the reddest bandpasses the differences are even larger due to the new prescrptions for TP-AGB stars that are incorporated in our models.

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