COMPARING DYNAMICAL AND STELLAR POPULATION MASS-TO-LIGHT RATIO ESTIMATES

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Abstract We investigate the mass-to-light ratios of stellar populations as predicted by stellar population synthesis codes and compare those to dynamical/gravitational measurements. In Bell & de Jong (2001) we showed that population synthesis models predict a tight relation between the color and mass-to-light ratio of a stellar population. The normalization of this relation depends critically on the shape of the stellar IMF at the low-mass end. These faint stars contribute significantly to the mass, but insignificantly to the luminosity and color of a stellar system. In Bell & de Jong (2001) we used rotation curves to normalize the relation, but rotation curves provide only an upper limit to the stellar masses in a system. Here we compare stellar and dynamical masses for a range of stellar systems in order to constrain the mass normalization of stellar population models. We find that the normalization of Bell & de Jong (2001) should be lowered by about 0.05-0.1 dex in $M/L$. This is consistent with a Kroupa (2001), Chabrier (2003) or a Kennicutt (1983) IMF, but does not leave much room for other unseen components.

Keywords: stars: mass function — galaxies: stellar content — galaxies: fundamental parameters — galaxies: kinematics and dynamics

1. Introduction

In Bell & de Jong (2001) we showed that stellar population models predict a strong correlation between an optical color of a stellar population and its mass-to-light ($M/L$) ratio (see also e.g., Bell et al. 2003; Portinari et al. 2004). We showed that the slope of this relation is rather insensitive to the exact details of the star formation history and chemical enrichment of the stellar population (except for recent star bursts) and to dust reddening, owing to the well-
known age/metallicity/dust degeneracy. Furthermore, the color–\(M/L\) slope is also rather insensitive to the IMF used. Yet, the normalization of the color–\(M/L\) relation is highly IMF dependent, shifting up and down depending on how many stars are present at the low-mass end of the stellar IMF (these stars contribute significantly to the mass of a population, but insignificantly to its luminosity and color).

In Bell & de Jong (2001) we used maximum disk rotation curves to constrain the normalization of the color–\(M/L\) relation. The predicted stellar population masses derived from the color–\(M/L\) relation should never over-predict the observed dynamical masses derived from rotation curves. However, while rotating gas in a disk galaxy is a very simple dynamical system and hence a clean constraint, rotation curves of disk galaxies have the disadvantage that they only provide an upper limit to \(M/L\) ratios once we accept that dark matter may be present in disk galaxies. There is no guarantee that there is no unseen matter contributing to the dynamical mass within the radius where the maximum disk is constrained, be it baryonic (e.g., cold molecular gas) or non-baryonic. Hence, rotation curves only provide an upper limit to the normalization of the color–\(M/L\) relation. Here we compare dynamical masses and masses predicted by stellar population modeling of a variety of stellar systems in order to constrain the normalization of the color–\(M/L\) relation\(^1\).

2. Comparing dynamical and population \(M/L\) estimates

In order to compare dynamical and stellar population masses we have to make a number of assumptions:

- The IMFs of the stellar populations in the different objects are the same, notwithstanding the large range in object scale sizes and masses involved.

- The stellar population models used are accurate in a relative sense (not necessary in absolute calibration).

- The stellar systems in question have not selectively lost (or accreted) stars in a particular mass range.

- Where necessary we use the HST Key Project distance scale.

We will now go through a number of dynamical/gravitational versus stellar population mass comparisons, and express the range of allowed population \(M/L\) ratios in terms of the IMF normalization used in Bell & de Jong (2001),

\(^1\)In principle, any of these systems could have a dark component co-spatial with the stellar light (in some cases this is rather unlikely), and hence all comparisons are strictly speaking upper limits to the relation.
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i.e. a Salpeter $x=1.35$ IMF between 0.1 and 125 $M_\odot$ reduced in mass by a factor 0.7$^2$.

**Globular Clusters** At first sight globular clusters seem ideal targets to compare dynamical and stellar population masses: their stellar populations, dust corrections and dynamics are simple, and they are unlikely to contain large amounts of dark matter near their centers. However, mass segregation has resulted in centers of clusters being dominated by massive stars, the outer parts by lower mass stars. The outer stars are subsequently more likely to be stripped by interaction with the galaxy, making it even harder to get a good sampling of the original full IMF. Detailed dynamical modeling of Galactic globular clusters shows clear evidence of these effects, with $M/L$ changing with radius (e.g., Gebhardt & Fischer 1995).

When we compute the dynamical core $M/L$ ratios of Galactic globular clusters following McLaughlin (2000) and compare those to single burst *PEGASE* (Fioc & Rocca-Volmerange 1997) models using the colors and metallicities of Harris (1996), we find that the dynamical $M/L$ values are much lower (by about 0.23 dex) than predicted by the single burst models of a 10–12 Gyr old population. Alternatively, we can follow a more simplified approach by using virial masses (Pryor & Meylan 1993), which are more representative of the total globular cluster. We find that the 12 Gyr stellar population masses are lower by 0.10 dex than the virial masses when using our Bell & de Jong (2001) IMF normalization, albeit with a large scatter of 0.20 dex rms (comparable to the uncertainties in the dynamical $M/L$ values).

In recent years it has also become possible to measure virial masses of globular clusters in other nearby galaxies. This has the advantage that it is easier to get integrated properties the globular clusters and many objects at the same distance, but as disadvantage the limited accuracy that can be reached, even with 8 m class telescopes. The results of extra-galactic globular clusters are still inconclusive, with dynamical masses of Cen A as measured by Martini & Ho (2004) being more massive than our stellar population model predictions by 0.08 dex, but the dynamical masses of M33 (Larsen et al. 2002) being 0.27 dex lower than predicted.

**Elliptical galaxies** Recently, Cappellari et al. (2006) have performed a detailed analysis of dynamical and stellar populations masses of a sample of early-type galaxies. Their integral field spectrograph SAURON data allows them to derive accurate dynamical masses using Schwarzschild modeling and stellar population masses using line-strength indices modeling. Using a Kroupa (2001) IMF and Vazdekis et al. (1999) stellar population synthesis models, they

$^2$We do not explicitly include a mass contribution for objects with masses less than 0.1 $M_\odot$; as argued later, the contribution from brown dwarf or planetary regime objects to the stellar $M/L$ is expected to be 0.04 dex or less.
find that old, fast rotating elliptical galaxies have dynamical and stellar population masses that are very similar. Younger, fast rotating elliptical galaxies have smaller stellar population masses than dynamical masses, but they can be made to agree by assuming that the young ages are the result of a superposition of a dominant, old massive population and a small, young population. However, slowly rotating, old massive elliptical galaxies seem to have higher dynamical than stellar population $M/L$ ratios, a discrepancy that cannot be solved by a superposition of young and old populations, because the population already is old according to the line indices.

Cappellari et al. (2006) argue that under the assumption that the IMF is the same for all galaxies this must mean that these massive, slowly rotating galaxies have a significant dark matter within their effective radius where the dynamical measure was made. However, once we accept that some elliptical galaxies must have a dynamically significant amount of dark matter in their central region, we cannot exclude that all elliptical galaxies have dark matter contributing to their central dynamics. Therefore, the comparison of stellar population and dynamical masses in elliptical galaxies becomes an upper limit to the normalization of the “IMF mass”, identical to the maximum disk rotation curve constraint. In terms of this mass normalization, this argues for a $\sim 0.05$ dex lower normalization that used by Bell & de Jong (2001), given that the Vazdekis models include masses down to 0.01 $M_\odot$.

**Maximum disk rotation curves:** As described above, we used maximum disk rotation curve limits to normalize the color–$M/L$ relation in Bell & de Jong (2001). In Kassin, de Jong & Weiner (2006) we have repeated this analysis, but we expanded the Verheijen (1997) Ursa Major cluster sample with 34 luminous galaxies and improved the treatment of shifting the mass models to another distance. We compared the maximum disk values to the updated color–$M/L$ relations of Bell et al. (2003) and find that the Bell & de Jong (2001) normalization is fully consistent with this expanded data set. The normalization may at best be 0.05 dex higher to account for the scatter in the color–$M/L$ relation.

**Minimum disk rotation curves:** While most galaxy rotation curves are fairly smooth, some show enough structure to allow determination of a lower limit to a stellar $M/L$ to explain these structures under the assumption that the dark matter component is smooth (e.g., Noordermeer et al. 2004). Such analysis is complicated by the unknown intrinsic distribution of dark matter, the effect of adiabatic contraction, and rotation curve uncertainties (including non-circular motions). Using NGC 157 (Kassin et al. 2006) we find a lower limit of -0.3 dex with respect to the Bell & de Jong (2001) normalization to explain the strongly declining rotation curve of this galaxy. However, the large asymmetries and hence large errorbars on the rotation curve of this galaxy limits the usefulness
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of this galaxy. More suitable systems (mainly early-type spiral galaxies with falling rotation curves) are studied by Noordermeer (2006).

**Disk velocity dispersions:** The mass and scale height distribution determine the vertical velocity dispersion of a self-gravitating disk. Thus, to determine a disk mass from a measured vertical velocity dispersion in a face-on system we have to make assumptions about the (unobservable) vertical stellar distribution, while for edge-on systems, where we can measure the vertical stellar distribution, we have to relate the observed radial and tangential velocity dispersion to the (unobservable) vertical velocity dispersion (Bottema 1997). Recently, Kregel et al. (2005) used velocity dispersions of a sample of 15 edge-on galaxies to determine a dynamical mass Tully-Fisher relation and compared it to the stellar population mass Tully-Fisher relation of Bell & de Jong (2001). They find an offset of about -0.24 dex, assuming a vertical-to-radial velocity dispersion ratio ($\sigma_z/\sigma_R$) of 0.6. However, the determined $M/L$ ratio scales quadratically with the poorly known $\sigma_z/\sigma_R$ ratio. To the best of our knowledge, only 3 measurements of $\sigma_z/\sigma_R$ have been made to date, ranging between 0.5 and 0.9 (Gerssen, Kuijken, & Merrifield 2000). Without substantially better understanding of the behavior of $\sigma_z/\sigma_R$ as a function of galaxy properties, it is unclear that one can place competitive constraints on stellar $M/L$ ratios using this method.

**Bar streaming motions:** A galactic bar moving through the interstellar medium creates streaming motions and often a shock, the size of which depends somewhat on the pattern speed of the bar, but mostly on the mass of the bar. Weiner et al. (2001; 2004) obtained $H\alpha$ velocity fields of NGC 4123 and NGC 3095 and modeled these with fluid-dynamical models. Their models only permit a limited range in stellar $M/L$, such that the galaxies are close to maximum disk. In Fig. 1 we compare the local bar colors and the derived $M/L$ values of these two galaxies to the stellar population models of a range in metallicity and with exponentially decaying star formation rates. We show the models normalized at the Bell & de Jong (2001) value on the left, reduced by 0.1 dex in $M/L$ on the right. The models cover a limited area in these diagrams, showing the age-metallicity degeneracy that makes the color–$M/L$ relation work in the first place.

We expect the central region to suffer from extinction, and we have plotted indicative dereddening vectors on the measured data points. These vectors were derived from Tully et al. (1998) global galaxy reddening values, and the extinction in the central region may be somewhat higher. The left panel, where the Bell & de Jong normalization is used, shows that the raw and reddening-corrected stellar $M/L$ ratios are consistent with the model normalization. The right-hand panel, with the model stellar $M/L$ values decreased by 0.1 dex compared to Bell & de Jong (2001), is just consistent with the reddening-corrected data. The bar streaming motions modeling therefore provides some of the
strongest constraints on our color–$M/L$ normalization, allowing only a range of $\sim 0.2$ dex.

Pérez et al. (2004) confirm the analysis of Weiner et al. (2001) to the extent that, for the two out of their sample of five galaxies for which they could derive $M/L$ constraints, the barred galaxies had to be close to maximum disk (at least 80% stellar mass contribution in bar region).

**Spiral arm streaming motions:** In a similar fashion, streaming motions can be used to estimate the mass in a spiral density wave. Clearly this is a more challenging exercise, as arm-induced shocks and streaming motions are much weaker than those induced by bars. Kranz et al. (2003) studied five high surface brightness galaxies with long-slit spectra and optical/near-IR surface photometry. They can only weakly constrain stellar $M/L$ (their Table 3), and find i) most of their sample have maximum disk $M/L$ values consistent with the Bell & de Jong calibration, and ii) most high $v_{\text{rot}}$ disks are consistent with close to maximum disk, whereas the lower rotation velocity disks could be substantially sub-maximal (with less than $\sim 60\%$ of the disk mass coming from stars within 2.2 disk scalelengths).

**Strong galaxy lensing:** Strong gravitational lensing provides an estimate of the gravitational mass within the lens area with rather straightforward modeling. To compare the gravitational mass of the lens with its stellar population mass we have to correct the observed colors using k-corrections or better yet, redshift the model spectra to the lens redshift and calculate a new color–$M/L$ grid in the observed bands. Furthermore, we have to realize that galaxies are younger at higher redshift and the color–$M/L$ relation will shift. For simplic-
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ity we can model this with exponentially declining star formation rate models (which becomes an increasingly poorer approximation at higher redshift, because starbursts will become relatively more important). Such exponentially declining models — started 12 Gyr ago — have color–$M/L$ relations in rest-frame colors that are decreased by 0.15 dex at redshift 1 compared to the $z=0$ relation.

To minimize these corrections a lensing galaxy at low redshift should be used in the gravitational to stellar mass comparison. Furthermore, the lensed images should be of small angular separation, surrounding only the central region of the lens galaxy, which is most likely to be dominated by stellar mass. We should keep in mind that any masses derived from lensing, like maximum rotation curves, only provides an upper limit to the stellar population mass estimates, as significant dark matter may be present in the centers of some galaxies as also suggested by the Cappellari et al. (2006) elliptical galaxies result.

Indications from the first studies to satisfy these criteria are encouraging. Smith et al. (2005) present an example of a low redshift ($z=0.0345$), tight lens, finding a $M/L_I \sim 1.8$, $M/L_B \sim 4.7$. Using the reported F475W and F814W observed magnitudes, galactic foreground corrections, and k-corrections assuming a non-evolving ancient galaxy template (solar metallicity and $\sim 12$ Gyr old), we find excellent agreement with the predicted stellar $M/L$ values, as usual accounting for gas recycling from ageing stellar populations ($M/L_{I,\text{pred}} \sim 1.8$, $M/L_{B,\text{pred}} \sim 4.5$). Koopmans et al. (2006) analyze an extensive sample of 15 lenses with $z=0.06$–$0.33$. In this case, the dynamically-derived total $M/L$ scale is compared with the lensing results, finding consistency (i.e., they have roughly cross-checked the dynamical mass scale — e.g., Cappellari et al.’s scale — with the lensing scale). A more careful, explicit test of the color-derived stellar mass scale with the lensing mass scale is clearly warranted.

3. Conclusions

In Fig. 2 we give an overview of all constraints derived in the previous section on stellar population $M/L$ values relative to an IMF normalization of Bell & de Jong (2001). The strongest constraints are currently provided by the Weiner et al. (2001, 2004) constraints from bar streaming motions. However, this constraint is derived from only two galaxies, and is therefore very susceptible to for instance errors in the distances to the galaxies. We have indicated in Fig. 2 the effect of 15% distance errors, which accounts for 0.075 dex offset in the $M/L$ IMF normalization. Another source of uncertainty lies in the stellar population modeling. The Padova isochrone tracks (Girardi et al. 2002) are used in many of the popular models (e.g., Charlot & Bruzual 2003; Fioc & Rocca-Volmerange 1997; Vazdekis 1999) and these models all give very
similar results in terms of the color–$M/L$ relation. However, a class of models based on the fuel consumption theorem that treats the late stages of stellar evolution differently are giving somewhat different results, especially in the infrared where AGB and RGB stars dominate (e.g., Maraston 2005). These models have indeed a slightly steeper slope in the color–$M/L$ relation, especially in the near-infrared, but surprisingly the normalizations of the different sets of models are very consistent in the intermediate color range where most of the normalization constraints are derived. Combining all constraints, we argue that the most likely normalization is about 0.05–0.1 dex lower than the Bell & de Jong (2001) normalization, i.e. a Salpeter $x=1.35$ IMF between 0.1 and 125 $M_\odot$ reduced in mass by a factor 0.6 (-0.22 dex).

This normalization is consistent with for instance the Kroupa (2001) or Chabrier (2003) IMFs (offset by about -0.25 dex with respect to Salpeter IMF) and a Kennicutt (1983) IMF (-0.3 dex). It leaves however not much margin for other unseen but known mass components in the dynamical comparisons. Stellar and substellar objects below our 0.1 $M_\odot$ mass limit could contribute up to 10% (0.04 dex) of the IMF mass. A significant molecular gas component in...
the inner part of spiral galaxies could push down the rotation curve constraint. However, it is satisfying to see that the current Galactic IMF estimates give stellar mass estimates in a wide range of objects that are fully consistent with their dynamical masses.

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