Synthetic stellar mass-to-light ratios for stellar populations

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**Abstract.** Evolutionary synthesis models for stellar populations of various ages and chemical compositions are constructed with the approach described in Maraston (1998), in which the Fuel Consumption Theorem is used to evaluate the energetics of Post Main Sequence stars. We present here the synthetic "stellar" mass-to-light ratios ($M^*/L$) in the $U, B, V, R, I, J, H, K$ photometric bands, as functions of age and chemical composition, for single burst populations. Taking into account the contribution by stellar dead remnants, the computed $M^*/L$ ratios can be directly compared to those measured in early-type galaxies. The dependence of $M^*/L$ ratios on the IMF slope is also explored. The most interesting result is that the $M^*/L_B$ ratio of a 15 Gyr stellar population is found to increase by nearly a factor of three, when the chemical composition rises from $[\text{Fe}/\text{H}] \sim -0.5$ to $[\text{Fe}/\text{H}] \sim +0.3$. This impacts on the interpretation of the tilt of the *Fundamental Plane* of cluster ellipticals in the $B$ band.

1. **Introduction**

Elliptical galaxies (Es) are not randomly distributed in the three-dimensional space defined by the observed parameters: central velocity dispersion $\sigma_0$, effective radius $r_e$ and the surface brightness $I_e$ within $r_e$. They occupy with very small dispersion a planar surface (Dressler et al. 1987; Djorgovski and Davis 1987), called the *Fundamental Plane* (FP). Thus the FP defines a correlation between the luminosity, size and dynamical mass of a galaxy. With the aim of a more transparent view on the physical properties of Es, Bender, Burstein & Faber (1992; hereafter BBF) analysed the Virgo and Coma cluster elliptical FP in the $B$-band, by introducing a convenient orthogonal coordinate system (known as the $\kappa$-space), in which the new variables are linear combinations of $\log \sigma_0^2$, $\log R_e$ and $\log I_e$. In this frame, the $\kappa_1$-$\kappa_3$ plane is an almost edge-on view of the FP (see BBF, Fig. 1). The main properties of the BBF Es FP are 1) the so-called *tilt*, i.e. the systematic increase of $\kappa_3$ along the FP ($\kappa_3 = 0.15\kappa_1 + \text{const}$) and 2) its tightness, i.e. the very small dispersion of $\kappa_3$, $\sigma(\kappa_3) \approx \pm 0.05$ at every location on the FP. Using the virial theorem, the $\kappa$-coordinates can be related to the total galaxy mass, $M = c_2 r_e \sigma_0^2$, by $\kappa_1 \propto \log M/c_2$ and $\kappa_3 \propto \log M/L_B c_2$. If the virial coefficient $c_2$ is constant for all the galaxies (or, Es form an homologous family), the observed FP tilt implies that $M/L_B$ increases by a factor $\sim 3$ with galactic mass. The physical origin of the FP tilt is still at the debate (see also Pahre et al., this volume), but it can be sought in two orthogonal directions:

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either it is due to a stellar population effect, in which case $M^*/L$ scales with the luminosity (mass) of the galaxies and $c_2$ is constant. Or structural/dynamical homology is broken, in which case $M^*/L$ is constant and $c_2$ varies along the galaxy sequence. The aim of this contribution is to explore the former option, the structural/dynamical one being extensively discussed in, e.g., Ciotti, Lanzoni & Renzini (1996).

From an observational point of view, the slope $\alpha$ of the FP scaling relation, $r_{\text{eff}} \propto \sigma_0 \, t_e^{\beta}$, is found to increase systematically with wavelength, from the $U$-band to the $K$-band (see the contribution by Pahre et al. in this volume and references therein). This points towards systematic variations of the stellar content along the Es sequence, which also gets support from systematic trends in colours and line strengths with galaxy luminosity (hence with $\kappa_1$).

The mass-to-light ratios of stellar populations change with age, chemical composition, and Initial Mass Function (IMF). The IMF effect has been explored by Renzini & Ciotti (1993). Their main conclusion is that a strong fine tuning is required to produce the observed tilt of the FP, preserving the constant thickness: the IMF should be virtually universal for a given galaxy mass, and yet exhibit a large trend with galaxy mass. A straightforward interpretation of the $\text{Mg}_2 - \sigma$ relation (see Bender, Burstein & Faber 1993) and the colour-magnitude relation (Bower, Lucey & Ellis 1992; see also Kodama, this volume) of Es is in terms of increasing metallicity along the galaxy sequence. This effect on $M^*/L$ is explored for the $V$-band in Renzini (1995). In this work, the effect of metallicity and age on the $M^*/L$ ratio is analysed for several photometric bands. This is part of a more extended work which aims at determining what fraction of the observed FP tilt is produced by stellar population effects, through the comparison of the FP at different wavelengths (Maraston & Renzini 1998, in preparation).

2. Models for stellar mass-to-light ratios

Models for Simple Stellar Populations (SSP) are computed with the evolutionary synthesis approach described in Maraston (1998; hereafter M98), in which the Fuel Consumption theorem (Renzini & Buzzoni 1986) is used to evaluate the energetic of Post Main Sequence (PMS) stars.

The input stellar tracks for the SSP models presented here are taken from Cassisi (private communication; see also Boni et al. 1997). They are computed by means of the FRANEC evolutionary code (see Chieffi & Straniero 1989). The range in metallicity is $[\text{Fe}/\text{H}] = [-1.3 \div 0.3]$, with helium-enrichment $\Delta Y/\Delta Z=2.5$; age varies from 3 Gyr to 15 Gyr. We refer to Maraston (1998, in preparation) for more details.

The IMF is assumed to follow the usual power-law, $\Psi(m) = A m^{-(1+x)}$. Besides the Salpeter slope ($x=1.35$), we explore the multislope case with a break at low masses, as recently suggested by Gould, Flynn & Bahcall (1997; hereafter GBF97) on the basis of HST observations of disk $M$ dwarfs. Depending on the mass range, the adopted slopes are: $x=0$ for $m \leq 0.6 M_\odot$, $x=1.21$ for $0.6 < m/M_\odot \leq 2$ and $x=1.35$ otherwise. The upper and lower mass cutoffs are fixed at 100 $M_\odot$ and 0.1 $M_\odot$ respectively in both cases. The synthetic $M^*/L_\lambda$ ratios contain the contribution by stellar remnants. As a stellar population ages, stars
progressively die, leaving remnants, that only contribute to the mass of the population. The mass lost in the form of ejected gas is supposed to be blown out of the stellar population. The total mass of an SSP of age \( t \), \( M^*(t) \), is thus obtained by convolving the stellar mass \( m^*(t) \) with the IMF, with \( m^*(t) = m_{\text{in}} \) for \( m_{\text{in}} \leq m_{\text{TO}}(t) \) and \( m^*(t) = m_{\text{R}} \) for \( m_{\text{in}} > m_{\text{TO}}(t) \). The quantities \( m_{\text{in}} \), \( m_{\text{TO}}(t) \) and \( m_{\text{R}} \) denote the initial Main Sequence mass, the turnoff mass and the remnant mass, respectively. For the remnant mass we adopt the same recipe as in M98 and Renzini & Ciotti (1993). We do not take the dependence of \( m_{\text{R}} \) on metallicity into account, since it implies difference in \( m_{\text{R}} \) of the order of \( \sim 10^{-2} M_\odot \).

At fixed age, \( M^*(t) \) is fairly insensitive to the metal content because \( m_{\text{TO}}(t) \) does not change appreciably with the chemical composition: for a 15 Gyr SSP, the variation of \( m_{\text{TO}}(t) \) is at most 0.15 \( M_\odot \). The \( M^*(t) \) computed with a Salpeter IMF is \( \sim 2.5 \) times greater than the one for the GBF97 IMF, since the latter contains less low-mass stars. Due to the slow evolution of \( m_{\text{TO}}(t) \) at old ages (\( t \gtrsim 1 \) Gyr), the influence of age on \( M^*(t) \) is very mild (see M98 for more details). In the age range \( 3 \div 15 \) Gyr, \( M^*(t) \) varies only by a factor of \( \sim 1.11 \), independent of the chemical composition.

### 2.1. The metallicity effect

![Figure 1. Synthetic \( M^* / L_\lambda \) in \( U, B, V, R, I, J, H, K \) photometric bands (from top to bottom), as functions of chemical composition.](image)

Fig. 1 shows the effect of metallicity on mass-to-light ratios. The \( M^* / L_\lambda \) ratio for various photometric bands (from \( U \) to \( K \), from top to bottom) as a function of metallicity (for 15 Gyr, Salpeter IMF SSPs) is shown. In general, the \( M^* / L_\lambda \) ratio increases with increasing metallicity. This pattern is more prominent in the \( U \)-band and decreases systematically with increasing wavelength, leading to a basically flat function in the \( J, H, K \) bands. Fig. 2 shows the systematic trend induced by metallicity on \( M^* / L_B \) and \( M^* / L_K \) (left-hand and right-hand panel, respectively), for the two different IMFs adopted. \( M^* / L_B \)
Figure 2. Synthetic $M^*/L_B$ (left-hand panel) and $M^*/L_K$ (right-hand panel) for 15 Gyr SSPs, as functions of chemical composition. Solid line is for a Salpeter IMF, dotted line for the GBF97 IMF (see the text).

is found to increase by a factor $\sim 3$ when $[\text{Fe}/\text{H}]$ increases from $\sim 1/3$ solar to two times solar. This range in metal content is roughly consistent with the one spanned by BBF Es (see Renzini 1995 and references therein), and the BBF FP in the $B$-band is tilted in a way that implies a $M/L_B$ variation of $\sim 3$ if the assumption of homology holds (see Sec. 1.). A pure metallicity effect thus suffices to explain the FP tilt observed in the $B$-band. If the low bright Es of BBF sample have $[\text{Fe}/\text{H}] \sim -0.3$ (half-solar) then the metallicity effect explains $\sim 68\%$ of the observed tilt. These results are for $\Delta Y/\Delta Z = 2.5$; it remains to be investigated if this is appropriate for the BBF Es (see Renzini 1995). To assess what fraction of the FP tilt is due to metallicity effects, the trend of the tilt with wavelength has to be examined. In fact, in the whole metallicity range here considered, the $M^*/L$ ratios in the IR are nearly constant (see Fig. 2, right-hand panel for the $K$ band). This scope will be pursued in a future paper (Maraston & Renzini, in preparation).

Fig. 2 shows that the two IMFs considered here manifest themselves only in the absolute values of $M^*/L_\lambda$, the systematic trends discussed above being not affected. This follows from $m_{TO}$ being fairly independent of the chemical composition (see Maraston 1998, in preparation for a wider discussion).

2.2. The age effect

Besides metallicity, age induces a systematic trend in the mass-to-light ratio. Here we briefly comment on this point. Fig. 3 shows the age effect on $M^*/L$ in the $B$ and $K$ bands (left-hand and right-hand panel, respectively) for the GBF97 IMF. For the fixed solar metallicity $[\text{Fe}/\text{H}]=0$, a variation by a factor of $\sim 3$ in $M^*/L_B$ is achieved, if age increases from $\sim 5$ Gyr to $\sim 15$ Gyr along the galaxy sequence. In this same age range, $M^*/L_K$ varies by a factor of $\sim 2.6$. To accept the age solution, a highly synchronisation in the formation process of
the Es of given luminosity (mass) is required, in order to preserve the small FP scatter (see Sec. 1.).

3. Conclusions

We have explored the systematic trends induced by metallicity and age on synthetic mass-to-light ratios, in which the contribution by stellar remnants is taken into account. The main result is that a pure metallicity effect is capable to explain the variation of $M^*/L_B$ observed in the BBF sample of cluster ellipticals, if $[\text{Fe/H}]$ increases from $\sim -0.5$ to $\sim +0.3$ along this galaxy sequence. $M^*/L$ ratios in the IR bands are instead predicted to display a flat trend with the chemical composition (cf. Fig. 2).

The slope of the FP is found to increase with wavelength (Pahre et al., this volume): the exponent $\alpha$ of the FP standard form $r_{\text{eff}} \propto \sigma_{0}^\alpha L_{e}^\beta$ is $\sim 1.4$ for the BBF FP in the $B$-band and $\sim 1.53$ for the Pahre et al. FP in the IR. The amplitude of the increase is thus modest, and a puzzling situation appears, in which other effects, like non-homology, have to be assumed to work differentially with wavelength, which obviously should not be the case. Moreover, a part of the tilt is certainly due to metallicity effects, as chemical composition varies along the Es sequence. We find indeed that these effects explain $\sim 70 - 100\%$ of the FP tilt in the $B$-band, depending on the real metallicity range spanned by the BBF sample. It is interesting to mention, however, that the tilt of the IR FP in the $\kappa$-space derived by Pahre et al. (1998) does not deviate from the BBF one in the $B$-band (see Sec. 1.).

If the IR FP is tilted in the way shown by Pahre et al., then it is entirely due to effects other than metallicity. But these effects have to show sign also in the $B$-band.
It would be highly useful measuring the FP correlations in different bands for the same sample of galaxies and using consistent fitting procedures.

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Discussion

ROCCA-VOLMERANGE: The giant branch of globular clusters is known to be very sensitive to metallicity, how can you explain the constancy of $M^*/L_K$ when $L_K$ is dominated by giant branches?

MARASTON: This effect is the result of the conspiracy between the amount of total energy at an SSP disposal and the effective temperatures at which this energy is emitted. For $\Delta Y/\Delta Z \sim 2.5$, passing from $[\text{Fe/H}] \sim -0.5$ to $[\text{Fe/H}] \sim +0.3$, the specific fuel burned in the Red Giant Branch by an SSP decreases by a factor $\sim 1.32$. The reason of this is simply that the percentage in mass of hydrogen, that is always the major source of energy, decreases from $\sim 0.75$ to $\sim 0.62$, for $\Delta Y/\Delta Z \sim 2.5$ and the values of $[\text{Fe/H}]$ here considered. But the fuel burned is released at cooler effective temperatures in a metal rich population. Thus the infrared emission is not too much metal dependent.

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