On breaking the age-metallicity degeneracy in early-type galaxies: infall versus star formation efficiency

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1 INTRODUCTION

In the ongoing quest for the Holy Grail of galaxy formation, suitable observables are sought to uniquely and unambiguously determine the star formation history of galaxies. Integrated broadband photometry targeting special regions of the spectral energy distribution such as the 4000Å break allows us to make a very good initial guess. The colour-magnitude relation observed in early-type galaxies (Faber 1973; Terlevich, Caldwell & Bower 2001) and its initial guess. The colour-magnitude relation observed in early-type passive evolution with redshift (Stanford, Eisenhardt & Dickison et al. 1995) sets a strong constraint on the duration of star formation. Furthermore, the colour-magnitude relation restricts the range of ages and metallicities of the stellar populations. We combine these two constraints with a model of star formation and chemical enrichment including infall and outflow of gas to find that the trend towards supersolar [Mg/Fe] in massive ellipticals excludes a pure metallicity sequence as an explanation of the colour-magnitude relation. An age spread is required, attributable either to a range of star formation efficiencies ($C_{\text{eff}}$) or to a range of infall timescales ($\tau_f$). We find that the inferred range of stellar ages is compatible with the small scatter and the redshift evolution of the colour-magnitude relation. Two alternative scenarios can explain the data: a fixed $\tau_f$ with a mass-dependent efficiency: $C_{\text{eff}} \propto M$, or a fixed $C_{\text{eff}}$ with mass-dependent infall: $\tau_f \propto 1/\sqrt{M}$. We conclude that the actual scenario may well involve a combination of these two parameters, with mass dependencies which should span the range of those given above.

Key words: galaxies: abundances — galaxies: evolution — galaxies: formation — galaxies: stellar content — galaxies: elliptical and lenticular, cD.

ABSTRACT

The correlation between [Mg/Fe] and galaxy mass found in elliptical galaxies sets a strong constraint on the duration of star formation. Furthermore, the colour-magnitude relation restricts the range of ages and metallicities of the stellar populations. We combine these two constraints with a model of star formation and chemical enrichment including infall and outflow of gas to find that the trend towards supersolar [Mg/Fe] in massive ellipticals excludes a pure metallicity sequence as an explanation of the colour-magnitude relation. An age spread is required, attributable either to a range of star formation efficiencies ($C_{\text{eff}}$) or to a range of infall timescales ($\tau_f$). We find that the inferred range of stellar ages is compatible with the small scatter and the redshift evolution of the colour-magnitude relation. Two alternative scenarios can explain the data: a fixed $\tau_f$ with a mass-dependent efficiency: $C_{\text{eff}} \propto M$, or a fixed $C_{\text{eff}}$ with mass-dependent infall: $\tau_f \propto 1/\sqrt{M}$. We conclude that the actual scenario may well involve a combination of these two parameters, with mass dependencies which should span the range of those given above.

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constraints on hierarchical clustering models, so that the baryon physics controlling star formation in galaxies must be significantly decoupled from the evolution of their dark matter halos.

The purpose of this paper is to make a combined analysis of broadband photometry (which is most sensitive to age and metallicity) and the [Mg/Fe] abundance ratio (which is sensitive to the duration of the bursting stages) in order to constrain the star formation history. One aspect is crucial to this paper; to determine the possible correlation of the various parameters that control star formation with a global property of the galaxy such as its total mass.

We focus on infall and outflow rates as well as on the star formation efficiency. A previous analysis using broadband photometry Ferreras & Silk (2000, paper I) concluded that there was still a degeneracy so that both outflow rates and star formation efficiencies could scale with galaxy mass. In this paper, we show that the addition of [Mg/Fe] to the analysis enables us to constrain the parameter space, ruling out pure metallicity sequences, and allowing either the star formation efficiency or the infall timescale to depend on galaxy mass.

2 A SIMPLE MODEL OF STAR FORMATION

We explore a one-zone model of star formation and chemical enrichment as described in Ferreras & Silk (2000). Each star formation history is determined by a set of four parameters: star formation efficiency ($C_{\text{eff}}$); fraction of gas and metals ejected in outflows ($B_{\text{out}}$), infall timescale ($\tau_f$) and formation epoch ($z_F$). We model the infall rate of primordial gas by a gaussian function whose spread is given by $\tau_f$ and whose epoch at maximum infall rate is given by the formation redshift $z_F$. We assume a Salpeter IMF in the mass range $0.1 < M/M_\odot < 60$. The model tracks the stellar, gas and metal components. The yields from type II supernovae (SNIa) are taken from Thielemann, Nomoto & Hashimoto (1996) for a range of progenitor masses. Type Ia supernovae (SNIa) are included using the prescription of Greggio & Renzini (1983) assuming a close binary composed of a white dwarf and a non-denegenerate companion in the (binary) mass range $3 - 16 M_\odot$. We refer the reader to Matteucci & Recchi (2001) for a comprehensive review of estimates of SNIa rates. The yields are taken from model

![Figure 1](image1.png)

**Figure 1.** Mass-weighted averages of stellar age (left), metallicity (center), and [Mg/Fe] (right), for a model with fixed formation epoch ($z_F = 3$) and for two different infall timescales: $\tau_f = 0.1$ Gyr (top) and 0.5 Gyr (bottom). The model is explored as a function of star formation efficiency ($C_{\text{eff}}$) and outflow fraction ($B_{\text{out}}$). The solid (dashed) contours are mass- (luminosity-) weighted values. Notice the observed range of [Mg/Fe] cannot be reproduced by the model with a longer infall timescale (bottom). The correlations of both [Fe/H] and [Mg/Fe] with galaxy mass can be explained by either a range of efficiencies or by a mixed $C_{\text{eff}} + B_{\text{out}}$ sequence. Notice that massive ellipticals require a non-negligible outflow fraction. A $B_{\text{out}}$ sequence (which translates into a pure metallicity sequence) is ruled out by the [Mg/Fe]-mass correlation.

![Figure 2](image2.png)

**Figure 2.** Same as figure 1 for a range of infall timescales ($\tau_f$) and outflow gas fraction ($B_{\text{out}}$) for two star formation efficiencies: $C_{\text{eff}} = 100$ (top) and 10 (bottom). In this case, no trajectory in the ($\tau_f$, $B_{\text{out}}$) can be found that explains both trends of [Fe/H] and [Mg/Fe] with galaxy mass. This implies star formation efficiency and outflows are the parameters strongly dependent on mass, whereas infall timescale should have a weaker dependence.
W7 in Iwamoto et al. (1999). Two elements are considered in this paper: magnesium and iron. The production of these two elements is remarkably different between both supernova types. A very significant amount of iron is produced in SNIa with respect to the α elements such as Mg. The mass contained in O-, Ne- and C-burning shells is too small compared with the mass in the Si-burning zone. This implies SNIa ejecta are dominated by the products of complete and incomplete Si-burning, i.e. a higher iron yield compared to the ejecta from core-collapse (type II) supernovae. Most of the iron produced in the latter falls inside a mass-cut that collapses to form the stellar remnant. Furthermore, the different timescale for the onset of both supernova types makes abundance ratios such as [Mg/Fe] very sensitive tracers of the duration of star formation. Short-lived and intense bursts of star formation generate stellar [Mg/Fe] that is depleted with respect to the SNII, resulting in enhanced [Mg/Fe]. On the other hand, a more extended enrichment history will allow the iron produced in SNIa’s to contribute significantly to the stellar metallicity, lowering the [Mg/Fe] ratio.

Hence, there is a direct – albeit non-trivial – correspondence between [Mg/Fe] and star formation duration. Similarly to analyses of metallicities performed to infer the star formation history, the absolute estimate of the age of star formation is highly dependent on the stellar yields used. Thomas et al. (1999) find a significant difference between estimates of the star formation timescale using the SNII yields from Woosley & Weaver (1995) and from Thielemann, Nomoto & Hashimoto (1996). The star formation timescale could be reduced by a factor up to 100 when using the yields from the former. The models of Thielemann et al. (1996) have a higher yield of Mg for stellar masses $M \sim 20 - 25 M_\odot$. This discrepancy is claimed to be caused by the different criterion used for convection. Furthermore, the models of Woosley & Weaver (1995) generate more iron (models B.C). Most of the Mg is produced during hydrostatic burning of the carbon shell. However, the mechanism for the production of $^{56}$Ni which decays into $^{56}$Fe is strongly dependent on the highly uncertain explosion mechanism. Throughout this paper we will use the yields from Thielemann and Nomoto & Nomoto (1996) for SNII. However, more work is definitely needed in this field if we want to make accurate estimates of the star formation timescales.

### 3 INFALL VERSUS EFFICIENCY

Figure 1 shows mass- (solid) and luminosity-weighted (dashed) contours of age (left), [Fe/H] (centre), and [Mg/Fe] (right) as a function of star formation efficiency ($C_{\text{eff}}$) and gas outflow fraction ($B_{\text{out}}$) for two infall timescales: $\tau_{\text{f}} = 0.1$ Gyr (top) and 1 Gyr. The formation epoch is $z_F = 3$, which is compatible with the birth rate of the formation redshift of the stellar populations in ellipticals from an analysis of the fundamental plane in clusters out to $z \sim 1.3$ (Van Dokkum & Stanford 2002). Short infall timescales are required if we want to reproduce the observed range of abundance ratios (e.g. Trager et al. 2000a; Kuntschner 2000), otherwise, choosing longer timescales would imply very low star formation efficiencies ($C_{\text{eff}} < 1$) in order to achieve low abundance ratios [Mg/Fe] $\sim 0.0 - 0.05$, and would generate young stellar populations which will not reproduce the redshift evolution of the observed slope and scatter of the colour-magnitude relation (Stanford et al. 1998). The parameter range shown in figures 1 and 2 is chosen to avoid such young stellar populations. The birthrate parameter $b = \psi / (\psi^\text{top})$ — for all models considered in this paper is below $b \leq 0.05$, i.e. the models never reach the lowest birthrates of early-type disks (Kennicutt, Tamblyn & Congdon 1994). The $\tau_{\text{f}} = 0.1$ Gyr model shown in figure 1 shows that a $B_{\text{out}}$ sequence (i.e. a horizontal line in the figure) – in which only the outflow fraction is assumed to vary with galaxy mass – could explain the mass-metallicity relation compatible with the colour-magnitude relation, as suggested by Kodama & Arimoto (1997). However, the constraint imposed by the correlation between [Mg/Fe] and galaxy mass excludes this as a possibility. A range of efficiencies (“$C_{\text{eff}}$ sequence”, vertical line) or a tilted “$C_{\text{eff}} + B_{\text{out}}$” sequence is needed to explain both correlations. Hence, the combined analysis of [Mg/Fe] and [Fe/H] poses very powerful constraints on the star formation history.

Figure 3 presents a similar plot to the previous figure. In this case a range of infall timescales and outflow fractions are explored. Two star formation efficiencies are considered: $C_{\text{eff}} = 50$ (top) and 5 (bottom). The figure shows that the range of abundance ratios could be explained by longer infall timescales in low-mass galaxies. Figures 4 and 5 illustrate the degeneracy between star formation efficiency and infall timescale, as both can reproduce a similar range of star formation histories. However, the chemical enrichment can be used to break this degeneracy, as seen in the central panel of figure 3. Models with long infall timescales give solar [Mg/Fe] but they also predict higher [Fe/H]. Hence, an explanation of the observed correlation between colour and [Mg/Fe] requires much larger outflow fractions if a range of infall timescales is assumed. Figure 3 further illustrates this point by overlaying contours of $U - V$ colour as predicted by population synthesis models (Bruzual & Charlot, in preparation) on [Mg/Fe] contours for a model with varying star formation efficiency (top) or in-
fall timescale (bottom). The hatched regions represent the area of parameter space that best explains massive ellipticals. The arrow gives the locus of points which track a sequence of galaxy masses. One can see from the figure that a remarkably larger range of outflow fractions is needed if a mass-independent star formation efficiency is assumed.

Figure 4 shows the observed correlation between \([\text{Mg/Fe}]\) and \(U - V\) colour from the sample of González (1993) later analyzed by Trager et al. (2000a). Several model predictions are shown as discussed in the text. The shaded region is a fit to the data and is used to determine the parameters shown in figure 5.

Figure 5 shows the mapping of this region in parameter space for the two most plausible scenarios, namely for a fixed infall timescale ("\(B_{\text{out}} + C_{\text{eff}}\) sequence", left) or for a fixed star formation efficiency ("\(B_{\text{out}} + \tau_f\) sequence", right). The \(U - V\) colour-magnitude relation of the Coma cluster is used in order to translate between color and absolute luminosity (Terlevich et al. 2001). A fixed star formation efficiency requires low-mass galaxies (\(M_V > -19\)) to have extremely high outflow fractions (\(B_{\text{out}} > 0.6\)). Models with a mass-dependent efficiency require a smaller range of outflows: \(0 < B_{\text{out}} < 0.4\). Doubtlessly, the real scenario will involve a range of all three parameters considered: \(B_{\text{out}}, C_{\text{eff}}\) and \(\tau_f\). However, the colour constraint on the range of outflows makes a stronger dependence of \(C_{\text{eff}}\) on mass more plausible. The dashed lines in the panels of figure 5 are guesses for the correlation with mass, using the observed dependence of \(M/L_V\) on galaxy mass in cluster ellipticals (Mobasher et al. 1999). The infall model (top right) gives a good fit to a \(\tau_f \propto 1/\sqrt{M}\) scaling, which can be theoretically motivated if we write the accretion timescale as the cross-section per unit mass:

\[
\tau_f \sim \frac{R^2}{M} \sim \frac{1}{M^{1/2} \rho^{3/2}}.
\]

If we assume a small range of formation redshifts, the correlation between \(\tau_f\) and mass is compatible with the model predictions shown in the top right panel of figure 5. On the other hand, the efficiency model (bottom left) favours a linear correlation with mass: \(C_{\text{eff}} \propto M\), a result which can be theoretically motivated by the effects of feedback on star formation (Silk 2002). The dashed lines in the middle panels span the plausible range of the correlation between mass and metallicity: \(1 - B_{\text{out}} \propto (Z) \propto M^{\alpha}\), with
We have explored the correlation between $U - V$ colour and [Mg/Fe] in early-type galaxies to determine the role of the galaxy mass in the formation of this type of galaxies. Infall timescale ($\tau_f \sim \frac{H}{\alpha}$) is also compatible with the data and the assumption of a mass-metallicity relation $Z \propto M^{1.3-0.1}$ favours this model. The accurate measurement of the mass-metallicity relation will be one of the key observables for disentangling infall timescales and star formation efficiency.

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