Star formation histories in early-type galaxies

D. Thomas
Universitäts-Sternwarte, Scheinerstr. 1, 81679 München, Germany

Abstract. I discuss the formation of $\alpha$-enhanced metal-rich stellar populations in the nuclei of luminous ellipticals. Based on hierarchical clustering, different galaxy formation scenarios, which imply different star formation histories, are considered. In contrast to the fast clumpy collapse mode, the late merger of two spiral galaxies fails to reproduce significantly $\alpha$-enhanced abundance ratios, unless the IMF is flattened. Following the star formation history predicted by semi-analytic models of hierarchical clustering for the average elliptical, solar abundance ratios are obtained with Salpeter IMF. According to the models, bright ellipticals in the field are expected to have significantly lower Mg/Fe ratios than their counterparts in a cluster.

1. Introduction

Theoretical population synthesis models based on solar abundance ratios predict – for a given Fe index – stronger Mg indices than measured in bright elliptical galaxies (e.g. Worthey, Faber & González 1992, Davies, Sadler & Peletier 1993). This result is generally interpreted such that the stellar populations hosted by these objects are $\alpha$-enhanced with respect to solar values.

In this paper I discuss different formation scenarios for early-type galaxies and seek under which conditions the observed [Mg/Fe] overabundance can be achieved.

1) A fast clumpy collapse is characterized by short star formation timescales and implies that ellipticals have formed early at high redshifts. This picture is observationally supported by the tightness of the fundamental plane relations (Dressler et al. 1987, Renzini & Ciotti 1993). Also the modest color evolution (Aragón Salamanca et al. 1993) and the evolution of the Mg-σ relation with redshift (Bender, Ziegler & Bruzual 1996, Ziegler & Bender) push the formation ages of cluster ellipticals to high redshift ($z > 2$). A clumpy collapse in the framework of hierarchical structure formation can also be considered as a refinement of the classical monolithic collapse (e.g. Matteucci 1994).

2) The scenario in which an elliptical is the outcome of two merging spirals, instead, emphasizes the relevancy of the merger process. Indeed, there are observational indications that merging must play an important role for the formation of early-type galaxies, since roughly 50 per cent of bright ellipticals host kinematically decoupled cores (Bender 1996).
3) The above models can be considered as two extreme cases of substantially
distinct formation scenarios. As a third option I discuss semi-analytic models
of hierarchical clustering, which describe galaxy formation in a cosmological
context (Kaufmann, White & Guiderdoni 1993, Cole et al. 1994). A priori, in
a bottom-up scenario the star formation history of a large object is expected
to be rather extended. Hence, the question arises if these kind of models are
compatible with [Mg/Fe] overabundance in luminous ellipticals (Bender 1997).
This issue is investigated here.

2. The chemical model

The basic constraints on the modeling, aimed to describe the stellar populations
in the central parts of bright ellipticals, are: (1) Achieving high (super-solar)
total metallicities ($Z > Z_\odot$), (2) producing an $\alpha$-enhancement of the order of
$[\alpha/Fe] \sim 0.2-0.4$ dex, as implied by the observations. The first requirement
comes from the observed nuclear Mg index and points towards either higher
yields (i.e. shallow IMF) in the central regions or to a scenario of \textit{enriched} inflow
(Edmunds 1990, Greggio 1997). The latter implies that the composite stellar
populations (CSPs) inhabiting the nuclear regions of ellipticals are characterized
by a metallicity distribution with a minimum metallicity $Z_m > 0$. For the \textit{fast clumpy collapse} and the \textit{merging spirals} I will show the results for $Z_m = Z_\odot$.
The second requirement constraints short time-scales or flatter IMF slopes, both
opportunities shall be discussed here. The suggestions of lowering the SN Ia rate
with respect to our Galaxy and selective mass loss mechanisms, instead, are not
explicitly considered in this paper.

In the models of the sections 2.1 and 2.2 a normalized amount of gas is
used up and transformed into stars within the star formation time-scale $\tau_{SF}$.
The rate of star formation is kept constant. For details of the modeling I refer
the reader to Thomas, Greggio & Bender (1998a, 1998b).

2.1. Fast clumpy collapse

On rather short time-scales ($\sim 1$ Gyr), massive objects are built up by merging
of smaller entities. Star formation takes place within these entities, on a larger
scale, however, the whole system participates in a general collapse. Fig. 1 gives
the $V$-light averaged Mg/Fe ratio in the stars for a family of models with different
star formation time-scales. The entire closed-box population with $Z_m = 0$
(dotted line) and the extracted metal-rich CSP with $Z_m = Z_\odot$ (solid line) are
shown. The result basically demonstrates that time-scales up to 1 Gyr yield
significant $\alpha$-enhancement for a Salpeter IMF slope ($x = 1.35$). The segregation
of the metal-rich population lowers $\langle [\text{Mg/Fe}] \rangle_V$ by less than $\sim 0.03$ dex,
but increases the metallicity of the CSP by $\sim 0.4$ dex (not shown in Fig. 1, see
Thomas et al. 1998b). A flattening of the IMF ($x = 0.7$) naturally allows for
longer time-scales, and in this case the cut-off at $Z_m = Z_\odot$ has no significant
effect on Mg/Fe.

2.2. Spiral merger

In this scenario I assume that the merger occurs when the two parent spirals
have converted a substantial fraction of gas into stars (i.e. two ‘Milky Ways’).
Figure 1.  V-light averaged Mg/Fe ratio in the stars for a family of models with different star formation time-scales and different IMF slopes.

Hence, most of the stars in the merging entities have formed in a continuous and long lasting (~ 10 Gyr) star formation process, leading to approximately solar abundance ratios. At merging, the (enriched) residual gas flows down to the center (Barnes & Hernquist 1996), where it experiences a violent episode of star formation in which the central population (considered here) forms on a short burst time-scale. Note that the global formation process, however, lasts ~ 10 Gyr or more. The minimum metallicity of the newly formed stars is solar by construction. For a family of different burst time-scales, the result is shown in Fig. 2 with Salpeter and flat IMF during the burst. Due to the huge amount of Fe created in the parent disk galaxy evolution before the merger, it is now impossible to form significantly α-enhanced CSPs with Salpeter IMF ($x = 1.35$), independent of the burst time-scale. In this case, a flattening of the IMF ($x = 0.7$) is required.

2.3. Hierarchical clustering

Semi-analytic models of hierarchical clustering can be placed between the two extreme cases discussed above. In these simulations structures are subsequently built up starting from small disk-like objects. An elliptical is formed when two disk galaxies of comparable mass merge. It is important to emphasize, that the bulk of stars forms at modest rates during disk galaxy evolution before this ‘major merger’ event (Kauffmann 1996, Baugh, Cole & Frenk 1996).

To follow the chemical evolution of such models during the entire formation history, I adopt the star formation history of the average cluster elliptical from Kauffmann (1996). Further details are described in Thomas (1998). In Fig. 3 the fractional contribution of the stars to the total V-band luminosity of the object is indicated by the solid line (plus signs show the contribution to the
V-light averaged Mg/Fe ratio in the stars for a family of models with different burst star formation time-scales and different IMF slopes during the burst. Pre-enrichment to solar abundance ratios before the merger is assumed (merger of two Milky Ways).

The $V$-luminosity weighted average Mg/Fe ratio of the respective composite stellar population is indicated by the diamonds for Salpeter IMF ($x=1.35$) and by the triangles for the flat case ($x=0.7$). Although exhibiting overabundant Mg/Fe ratios at the early stages of the evolution (i.e. the first 1–2 Gyr), $\langle [\text{Mg/Fe}] \rangle_V$ decreases with time and saturates at a roughly solar level after $\sim 10$ Gyr. The star formation history of the average elliptical as provided by hierarchical models does not lead to $\alpha$-enhancement, unless the IMF is significantly flattened.

In the Kauffmann (1996) models, the stellar populations of bright cluster ellipticals exhibit ages around 11–12 Gyr, and are consequently somewhat older than the average elliptical with an age of 10.5 Gyr. This implies a star formation history which is more skewed towards early times and therefore yields higher, probably super-solar Mg/Fe ratios. Note that, given their short formation times (1–2 Gyr), bright cluster ellipticals form in a scenario which appears similar to the fast clumpy collapse. The stellar populations of bright field ellipticals, instead, are predicted by the models to be younger by roughly 5 Gyr (Kauffmann 1996). These objects should therefore – owing to the more extended star formation history – exhibit significantly smaller Mg/Fe ratios than their counterparts in clusters.

3. Summary

(a) The two distinct formation scenarios, fast clumpy collapse and merging spirals, yield significantly different abundance ratios.
Figure 3. The star formation history of an average elliptical galaxy. The histogram shows the fractional contribution to the total $V$-light (plus signs: total mass) from each stellar population of a specific age. The underlying $V$-luminosity averaged abundance ratio $\text{Mg/Fe}$ in the stars is indicated by the diamonds (Salpeter IMF) and triangles (flat IMF).

(b) In contrast to the fast clumpy collapse scenario, the late merger of two spirals yields $\alpha$-enhanced populations, only if a shallow IMF is assumed.

(c) The star formation history of the average elliptical as specified by hierarchical clustering models leads to solar abundance ratios.

(d) Such models predict significantly higher Mg/Fe ratios in bright cluster ellipticals than in bright field ellipticals.

Acknowledgments. This work was supported by the "Sonderforschungsbereich 375-95 für Astro-Teilchenphysik" of the Deutsche Forschungsgemeinschaft.

Discussion

J. González: Can you comment on our present knowledge of stellar yields? Which ones did you use and why?

D. Thomas: The theoretical yields from Type II supernovae are still affected by many uncertainties, particularly magnesium and iron. As a consequence,
conclusions from chemical evolution models are principally weakened. However, the model and the nucleosynthesis can and should be calibrated on the chemical evolution of the solar neighborhood. I am using the yields from Thielemann, Nomoto & Hashimoto (1996), since they lead to the best reproduction of the abundance patterns in our Galaxy.

R. Bower: In what you discussed, you used a closed box model for chemical evolution. But in the hierarchical galaxy formation models, the inflow and outflow of gas are extremely important. How does this affect your conclusions?

D. Thomas: In case of hierarchical clustering models, I only discussed abundance ratios of elements with no primordial origin. As long as selective loss mechanisms etc. play a minor role, my conclusions on the Mg/Fe ratio are not affected. But I agree that a more detailed study of chemical enrichment in the hierarchical models is necessary to enable more reliable quantitative statements on abundance ratios.

References

Aragón Salamanca, A., Ellis, R. S., Couch, W. J., & Carter, D. 1993, MNRAS, 262, 764
Barnes, J. E. & Hernquist, L. 1996, ApJ, 471, 115
Baugh, C. M., Cole, S., & Frenk, C. S. 1996, MNRAS, 283, 1361
Bender, R. 1996, in New Light on Galaxy Evolution, R. Bender & R. L. Davies, Dordrecht: Kluwer Academic Publishers, 181
Bender, R. 1997, in The second Stromlo Symposium: The nature of elliptical galaxies, M. Arnaboldi, G. S. Da Costa, & P. Saha, Provo: Brigham Young University, 11
Bender, R., Ziegler, B. L., & Bruzual, G. 1996, ApJ, 463, L51
Cole, S., Aragón-Salamanca, A., Frenk, C. S., Navarro, J., & Zepf, S. 1994, MNRAS, 271, 781
Davies, R. L., Burstein, D., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R. J., & Wegner, G. 1987, ApJS, 64, 581
Davies, R. L., Sadler, E. M., & Peletier, R. F. 1993, MNRAS, 262, 650
Edmunds, M. G. 1990, MNRAS, 246, 678
Greggio, L. 1997, MNRAS, 285, 151
Kauffmann, G. 1996, MNRAS, 281, 487
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Matteucci, F. 1994, A&A, 288, 57
Renzini, A. & Cioffi, L. 1993, ApJ, 416, L49
Thomas, D. 1998, MNRAS, submitted
Thomas, D., Greggio, L., & Bender, R. 1998a, MNRAS, 296, 119
Thomas, D., Greggio, L., & Bender, R. 1998b, MNRAS, submitted
Worthey, G., Faber, S. M., & González, J. J. 1992, ApJ, 398, 69
Ziegler, B. L. & Bender, R. 1997, MNRAS, 291, 527