The metallicity distribution of the stars in elliptical galaxies

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Elliptical galaxies probably host the most metal rich stellar populations in the Universe. The processes leading to both the formation and the evolution of such stars are discussed by means of a new multi-zone photo-chemical evolution model, taking into account detailed nucleosynthetic yields, feedback from supernovae, Pop III stars and an initial infall episode. Moreover, the radial variations in the metallicity distribution of these stars are investigated by means of G-dwarf-like diagrams.

By comparing model predictions with observations, we derive a picture of galaxy formation in which the higher is the mass of the galaxy, the shorter are the infall and the star formation timescales. Therefore, the stellar component of the most massive and luminous galaxies might attain a metallicity $Z \geq Z_\odot$ in only 0.5 Gyr.

Each galaxy is created outside-in, i.e. the outermost regions accrete gas, form stars and develop a galactic wind very quickly, compared to the central core in which the star formation can last up to $\sim 1.3$ Gyr. This finding will be discussed at the light of recent observations of the galaxy NGC 4697 which clearly show a strong radial gradient in the mean stellar $\langle Mg/Fe \rangle$ ratio.

1. Introduction

Metallicity gradients are characteristic of the stellar populations inside elliptical galaxies. Evidences come from the increase of line-strength indices (e.g. Carollo et al., 1993; Davies et al., 1993; Trager et al., 2000) and the reddening of the colours (e.g. Peletier et al. 1990) towards the centre of the galaxies. The study of such gradients provide insights into the mechanism of galaxy formation, particularly on the duration of the chemical enrichment process at each radius. Metallicity indices, in fact, contain information on the chemical composition and the age of the single stellar populations (SSP) inhabiting a given galactic zone. Pipino & Matteucci (2004, PM04) showed that a galaxy formation process in which the most massive objects form faster and more efficiently than the less massive ones can explain the photo-chemical properties of ellipticals, in particular the increase of $[Mg/Fe]$ ratio in stars with galactic mass (see Matteucci, this conference, and references therein). PM04 suggested that a single galaxy should form outside-in, namely the outermost regions form earlier and faster with respect to the central parts. A natural consequence of this model and of the time-delay between the production of Fe and that of Mg is that the mean $[Mg/Fe]$ abundance ratio in the stars should increase with radius. Pipino et al. (2006, PMC06) compared PM04 best model results with the very recent observations for the galaxy NGC 4697 (Mendez et al. 2005), and found them in excellent agreement.

2. The model

The chemical code adopted here is described in full detail in PM04 and PMC06, where we address the reader for more details. This model is characterized by: Salpeter (1955) IMF, Thielemann et al. (1996) yields for massive stars, Nomoto et al. (1997) yields for type Ia SNe and van den Hoek & Groenewegen (1997) yields for low- and intermediate-mass stars (the case with $\eta_{AGB}$ varying with metallicity). Here we present our analysis of
Figure 1. “G-dwarf” distributions for \([Z/H]\) in luminosity (solid line) and mass (dotted line). Left column: values at 0.1\(R_{\text{eff}}\). Right column: values at 1\(R_{\text{eff}}\). The plots are presented in the same scale in order to better appreciate the differences among the different distributions.

A \(\sim 10^{11}M_\odot\) galaxy (PM04 model IIb), considered representative of a typical elliptical, unless otherwise stated.

The model assumes that the galaxy assembles by merging of gaseous lumps (infall) on a short timescale and suffers a strong star burst which injects into the interstellar medium a large amount of energy able to trigger a galactic wind, occurring at different times at different radii. After the development of the wind, the star formation is assumed to stop and the galaxy evolves passively with continuous mass loss.

3. Results and discussion

From the comparison between our model predictions (Fig. 1) and the observed G-dwarf-like diagrams derived at different radii by Harris & Harris (2002, see their fig. 18) for the elliptical galaxy NGC 5128, we can derive some general considerations. The qualitative agreement is remarkable: we can explain the slow rise in the \([Z/H]\)-distribution as the effect of the infall, whereas the sharp truncation at high metallicities is the first direct evidence of a sudden and strong wind which stopped the star formation. The suggested outside-in formation process reflects in a more asymmetric shape of the G-dwarf diagram at larger radii, where the galactic wind occurs earlier (i.e. closer to the peak of the star formation rate), with respect to the galactic centre.

From a quantitative point of view, properties such as the stellar metallicity distribution of the CSP inhabiting the galactic core, allow us to study the creation of mass-metallicity relation (see Matteucci, this conference), which is typically inferred from the spectra taken at \(\sim 0.1\) effective radius. In Fig. 2 we plotted the time evolution of the mass-metallicity relation in the stars (which reflect the average chemical enrichment of the galactic core as seen at the present day; dashed line) and in the gas (which, instead, is closer to the composition of the youngest SSP, thus being more indicative of a high redshift object; solid line). The mean Fe abundance in the stellar component can reach the solar value in only 0.5 Gyr, making ellipticals among the most metal-rich objects of the universe.

On the other hand, at variance with the G-dwarf-like diagrams as a function of \([Z/H]\) (and \([Fe/H]\)), abundance ratios such as \([\alpha/Fe]\) have narrow and almost sym-
metric distributions. This means that, also from a mathematical point of view, the $\frac{[\alpha/Fe]}{[Z/H]}$ ratio are representative of the whole CSP (PMC06). The robustness of the $\frac{[\alpha/Fe]}{[Z/H]}$ ratios as constraints for the galactic formation history is testified by the fact that $[\langle \alpha/Fe \rangle] \simeq \langle \alpha/Fe \rangle$, having very similar distributions. In particular, we find that the skewness parameter is much larger for the $[Z/H]$ and $[Fe/H]$ distributions than for the case of the $[\alpha/Fe]$ one, by more than one order of magnitude. Moreover, the asymmetry increases going to large radii (see Fig. 1, right panel), up to a factor of $\sim 7$ with respect to the inner regions. Therefore, it is not surprising that the $[< Z/H >]$ value does not represent the galaxy at large radii, and hence, we stress that care should be taken when one wants to infer the real abundances of the stellar components for a galaxy by comparing the observed indices (related to a CSP) with the theoretical ones (predicted for a SSP). Only the comparison based on the $[< \alpha/Fe >]$ ratios seems to be robust.

Another possible source of discrepancies is the fact that luminosity-weighted averages (which are more closely related to the observed indices) and mass-weighted averages (which represent the real distributions of the chemical elements in the stellar populations) might differ more in the most external zones of the galaxy (compare the panels in Fig. 1). All these considerations result in the fact that the chemical abundance pattern used by modellers to build their SSPs, might not necessary reflect the real trends. Therefore, the interpretation of line strength indices in term of abundances, can be seriously flawed (see PMC06 for further details).

The analysis of the radial variation in the CSPs inhabiting elliptical galaxies seems to be promising as a powerful tool to study ellipticals. Pipino, Puzia & Matteucci (in preparation), make use of the G-dwarf like distributions predicted by PMC06 to explain the multimodality in the globular cluster (GC) metallicity distribution as well as their high $\alpha$ enhancement (Puzia et al. 2006). In particular, preliminary results show that the GC distribution as function of $[Fe/H]$ for the whole galaxy can be constructed simply by combining distributions as those of Fig. 1 (typical of different radii), once they had been rescale by means of a suitable function (of time and metallicity) which links the global star formation rate to the globular cluster creation. Neither a need of an enhanced GC formation during mergers nor a strong role of the accretion of external objects, seem to required in order to explain the different features of the GC metallicity distributions.

Since globular clusters are the closest approximation of a SSP, we expect that this tec-
4. Concluding remarks

A detailed study of the chemical properties of the CSPs inhabiting elliptical galaxies as well as the change of their properties as a function of both time and radius, allow us to gather a wealth of information. Our main conclusions are:

- Both observed and predicted G-dwarf like distributions for ellipticals show a sharp truncation at high metallicities that, in the light of our models, might be interpreted as the first direct evidence for the occurrence of the galactic wind in spheroids.
- The stellar component of the most massive and luminous galaxies might attain a metallicity $Z \geq Z_\odot$ in only 0.5 Gyr.
- PM04’s best model prediction of increasing $<\alpha/Fe>$ ratio with radius is in very good agreement with the observed gradient in $[\alpha/Fe]$ of NGC 4697. This strongly suggests an outside-in galaxy formation scenario for elliptical galaxies that show strong gradients.
- By comparing the radial trend of $<Z/H>$ with the observed one, we notice a discrepancy which is due to the fact that a CSP behaves in a different way with respect to a SSP. In particular the predicted gradient of $<Z/H>$ is flatter than the observed one at large radii. Therefore, this should be taken into account when estimates for the metallicity of a galaxy are derived from the simple comparison between the observed line-strength index and the predictions for a SSP, a method currently adopted in the literature.
- Abundance ratios such as [Mg/Fe] are less affected by the discrepancy between the SSPs and a CSP, since their distribution functions are narrower and more symmetric. Therefore, we stress the importance of such a ratio as the most robust tool to estimate the duration of the galaxy formation process.
- Our results are strengthened by the comparison between our G-dwarf diagrams to metallicity distribution of the globular clusters residing in ellipticals.

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