Constructing the Universe with Clusters of Galaxies, IAP 2000 meeting, Paris (France) July 2000
Florence Durret & Daniel Gerbal eds.

LATE STAR FORMATION IN EARLY-TYPE CLUSTER GALAXIES

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1 The star formation history of early-type galaxies

The complicated dynamical history of early-type systems hints at a similarly complex star formation process. Currently, optical and near-infrared observations at low and moderate redshifts of elliptical galaxies are suggestive of an old stellar population with a small age spread, generated in an early and intense burst of star formation. However, some of these galaxies show enhanced Balmer absorption lines even in nearby clusters such as Coma (Caldwell et al. 1993), indicative of recent periods of star formation. Unfortunately, an estimate of the mass fraction in young stars has so far proved a rather qualitative endeavor. Age estimates using different spectral indices (Kuntschner 2000; Trager et al. 2000) are complicated by the presence of young stars, whose small mass-to-light ratios can significantly alter the observed (luminosity-weighted) age with respect to a — more physically meaningful — mass-weighted age. Observed mass-to-light ratios represent an interesting complement to spectral indices (Ferreras & Silk 2000a). However, estimates are hard to obtain, and are strongly model dependent.

We present an alternative approach to quantifying recent star formation using the near-ultraviolet (NUV) spectral window around rest-frame 2000Å . Figure 1 shows the time evolution of the spectral energy distribution of a simple stellar population with solar metallicity according to the models of Bruzual & Charlot (2000) and Yi (Yi et al. 1999). The filters shown are the HST/WFPC2 passbands used in Ferreras & Silk (2000b; hereafter FS00) who targeted cluster Cl0939+4713 ($z = 0.41$) looking for recent star formation with the technique presented here. In the figure, the filters (F300W and F702W) are shifted to the rest-frame of the cluster. One can see that the bluer filter (centered around rest-frame 2000Å) collects light from young main sequence stars, whereas the red passband approximately traces total stellar mass, so that F300W$-$F702W color is a sensitive indicator of recent star formation.

2 Is near ultraviolet light a reliable stellar clock ?

Even though the spectral energy distribution around rest-frame 2000Å is very sensitive to recent star formation, older stellar populations may contribute significantly in this spectral range. The UV upturn found in local elliptical galaxies (e.g. O'Connell 1999) is a feature caused by a

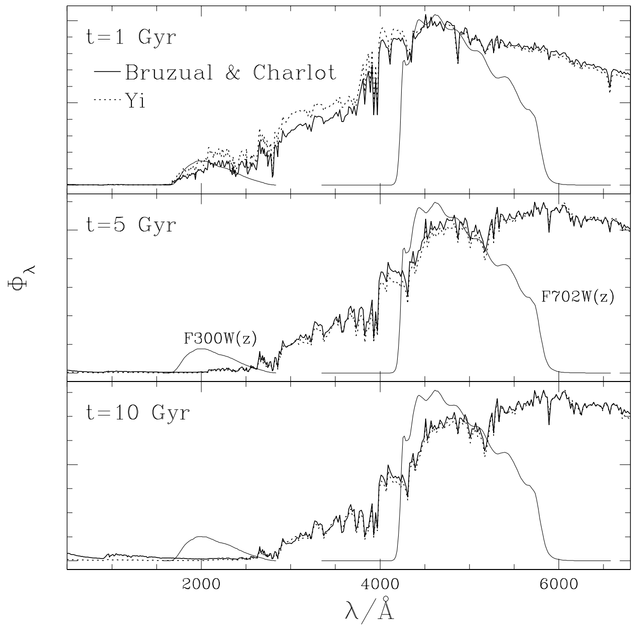

Figure 1: Spectral energy distributions for three different ages according to the population synthesis models of Bruzual & Charlot (solid) and Yi (dotted). Also shown are the HST/WFPC2 filters used in the observations of Cl0939+4713 ($z = 0.41$) done by Ferreras & Silk (2000b) shifted to rest-frame.

population of core-helium burning stars, namely horizontal branch (HB) stars and their progeny. It is still a matter of debate whether the upturn is caused either by low- or high-metallicity HB stars. Furthermore, the contribution to NUV light from post-asymptotic giant branch stars becomes more important with lookback time than that of HB stars (Lee et al. 1999). Modelling these late stages of stellar evolution is complicated by various factors like metallicity or mass loss during the red giant branch phase. However, the presence of young stars on the main sequence, even at low mass fractions will overwhelm the NUV flux with respect to older populations.

Figure 2 shows the predictions of the two population synthesis models described above. Yi's models include in detail the evolution of horizontal branch stars. The rest-frame $U-V$ and $V-K$ colors are compared, as well as F300W$-$F702W color at $z = 0.4$, which is the key observable in the analysis of cluster Cl0939+4713. One can see that the disagreement is significant at late stages, when core-helium burning stars dominate the contribution in the NUV spectral window. However, given the redshift of the cluster, the ages of the stellar populations cannot be older than the age of the universe at that epoch, which is $\sim$ 9 Gyr for any reasonable cosmology. Hence, even though the discrepancies caused by a different treatment of stellar evolution may alter the quantitative result, any galaxy bluer than F300W$-$F702W< 2 must have some fraction of stars younger than 1–2 Gyr.

It is worth emphasizing that studies of local ellipticals in the NUV use $m(1500) - V$ color — where $m(1500) = -2.5 \log F_{1500} - 21.1$ and F_{1500} is the mean flux at $\lambda = 1500$Å in units of erg s^{-1}cm^{-2}Å^{-1} — to estimate the strength of the upturn. Figure 1 shows that the NUV contribution from young A-type stars on the main sequence is centered around 2000Å in the rest-frame, whereas the flux at $\lambda \sim 1500$Å from these stars is rather weak. Hence, the spectral window detected by $m(1500)$ is more sensitive to evolved stellar populations. This could suggest the lack of early-type system detections in cluster Cl0939+4713 ($z = 0.41$) observed by Buson et al. (2000) with HST/WFPC2 through the F218W passband, which corresponds to $\lambda \sim 1550$ Å in the rest-frame. At a lookback time of 4.4 Gyr – for a flat, Λ-dominated cosmology with

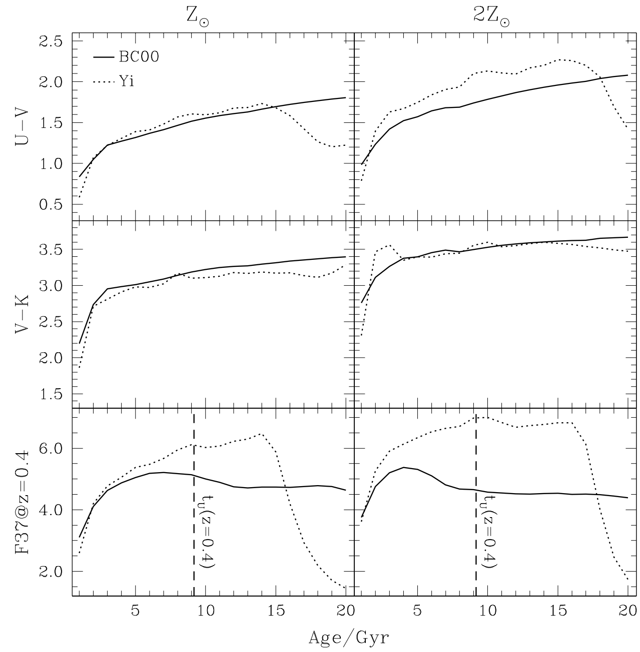

Figure 2: Comparison of the predictions from the models of Bruzual & Charlot (solid) and Yi (dotted) for three broadband colors as a function of age: $U-V$ (*top*) and $V-K$, both in the rest-frame, as well as F300W−F702W (*bottom*) at the redshift of cluster Cl0939+4713 ($z=0.41$).

$\Omega_m = 0.3$ and $H_0 = 70$ km s^{-1}Mpc^{-1} — one should expect a significant "switching-off" of the UV upturn in ellipticals at that redshift. Unfortunately, the limiting magnitude achieved in the 28ks exposure through the F218W filter is not deep enough to confirm this. However, it strengthens our hypothesis that the light passing through the F300W filter in the 42 detections of early-type systems observed by FS00 in the same cluster must come from young stars.

3 The NUV−Optical color-magnitude relation of cluster early-type galaxies

The NUV−optical color magnitude relation of cluster Cl0939+4713 is shown in Figure 3 (from FS00). The optical colors — observed by Dressler & Gunn (1992) — feature a remarkably tight scatter, similar to other clusters at moderate redshifts (Stanford et al. 1998). The tightness of the optical color-magnitude relation is interpreted as evidence towards a single burst scenario at high redshift ($z_F > 2$). The prediction for a single-burst model which evolves into the color-magnitude relation observed in local clusters is shown as a solid and dashed line for a formation redshift of $z_F = 10$ and 1, respectively. These two scenarios are incompatible with the data, the scatter towards blue NUV−optical colors is an indicator of recent star formation. Even though the figure suggests a steepening of the slope with respect to a single burst scenario, the detection limit of the images (shown in the figure as a shading, at a 4σ confidence level) is only good enough to imply an increased color scatter at faint magnitudes.

The analysis performed in FS00 assumes a simple star formation history consisting of two simple stellar populations: an old one formed at $z_F = 3$; and a younger one whose age (t_Y) and fractional contribution in stellar mass (f_M) is left as a free parameter. Figure 4 shows color contours in this 2-dimensional parameter space. Colors bluer than F300W−F702W<2 require a significant reduction of the luminosity-weighted age with respect to a monolithic star formation process. The fractional age reduction — defined as $\Delta\tau_V \equiv 1 - t_V/t_O$, with t_V and t_O being the luminosity-weighted age and the age of the old stellar population, respectively — is shown in

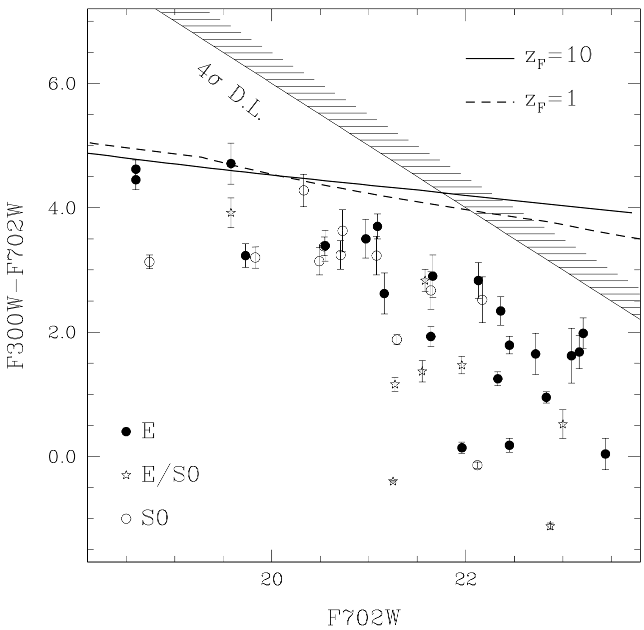

Figure 3: NUV−Optical color-magnitude relation of early-type systems in cluster Cl0939+4713. The shaded line gives the 4σ detection limit. The solid and dashed lines correspond to a dustless pure metallicity sequence of galaxies formed at a redshift of $z_F = 10$ and 1, respectively, using the $U - V$ vs M_V color-magnitude relation of local clusters as constraint.

Figure 4 at three values: 25, 50 and 75%.

Hence, the results found in cluster Cl0939+4713 cannot be reconciled with a simple monolithic formation scenario, and a process relating total luminosity and late star formation must be considered. The limiting magnitude of the images used in this analysis prevents us from concluding that the slope of the NUV−optical color-magnitude relation is much steeper than the prediction for a standard scenario of formation in a single burst. However, the remarkable scatter at faint magnitudes is a clear sign that many low mass galaxies might be undergoing a more interesting star formation history. More speculatively yet, taking the color-magnitude relation at face value implies a trend towards larger young stellar masses in fainter galaxies. This can be caused by several mechanisms such as a lower star formation efficiency in less massive galaxies, or a stronger fountain effect in these galaxies which causes "trickles" of star formation at late epochs. The consequences of these mechanisms for the predicted spectrophotometry can be very important in the search for high redshift early-type systems.

This paper also aims at drawing the attention of the extragalactic astrophysics community towards *rest-frame NUV imaging as a powerful tool for shedding light on recent processes of star formation*. This is especially interesting at moderate and high redshifts, for which rest-frame 2000Å shifts into the spectral range of optical cameras. A combined effort along with some targeted narrow waveband spectral indices (mainly Balmer absorption) can determine the contribution from young stars to a reasonable level of accuracy.

Acknowledgments

IF is supported by a grant from the European Community under contract HPMF-CT-1999-00109. We would like to thank Stéphane Charlot and Sukyoung Yi for very useful comments and for making available their population synthesis models.

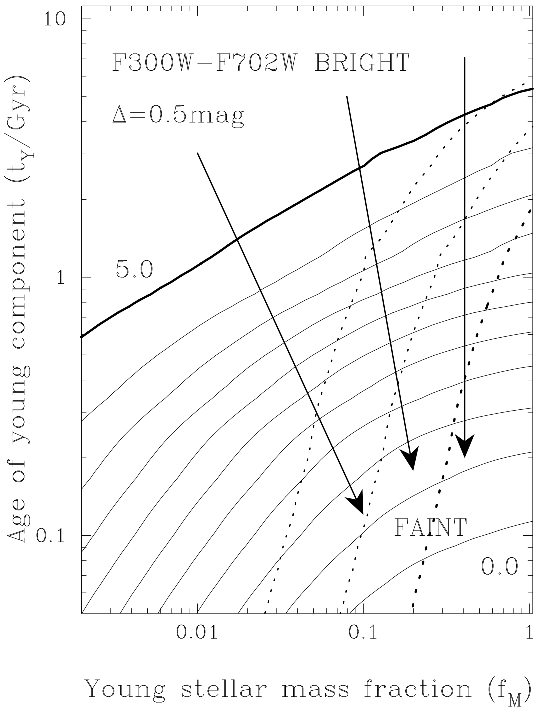

Figure 4: Contours of F300W−F702W color as a function of a simple two-burst star formation history described by two parameters $\{f_M, t_Y\}$ (see text). The observed blue colors at the faint end of the color-magnitude relation can only be explained by a significant reduction in the luminosity-weighted age ($\Delta\tau_V$) caused by the younger population. The dotted lines are contours of $\Delta\tau_V = 25, 50$ and 75% (thick).

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