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Galaxy populations in simulated clusters of galaxies

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Abstract. Cosmological LambdaCDM TreeSPH simulations of the formation and evolution of galaxy groups and clusters have been performed. The simulations include: star formation, chemical evolution with non-instantaneous recycling, metal dependent radiative cooling, strong star burst and (optionally) AGN driven galactic super winds, effects of a meta-galactic UV field and thermal conduction. The properties of the galaxy populations in the two richest clusters are discussed: global star formation rates of the cluster galaxies, the total K-band luminosity, the galaxy luminosity functions at z=0 and their redshift evolution, the colour-magnitude relation ("red sequence") as resulting from metallicity effects, and the role of the IMF in reproducing colours and abundances of the stellar populations.

1. Introduction

Non–gravitational heating and radiative cooling have been extensively recoursed to in the literature in order to complete the basic gravity-only driven scenario describing the thermal behaviour of the ICM, which is unable to reproduce the scaling relations observed between L_X, T and S.

So far few hydrodynamical simulations have been performed which were able to pursue at the same time and in a self–consistent way the target of realistically modelling the ICM dynamics by including both non-gravitational heating/cooling (complete with feedback/star formation) *and* metal enrichment directly springing from chemically following up the stellar feedback itself (e.g. Tornatore *et al.*2004). Moreover, only recently simulations have reached a level of sophistication adequate to even trace star formation and related effects in individual galaxies, coupled with the chemical enrichment of the ICM by galactic winds.

In this series of papers (Romeo *et al.*, 2005 = Paper II; Sommer-Larsen *et al.*, 2004 = Paper III), we present an analysis of the properties of the galaxy population of clusters as predicted directly from cosmological simulations that follow detailed baryonic physics, gas dynamics and galaxy formation and evolution. The resolution for such N–body + hydrodynamical simulations cannot reach the extent of resolving galaxies at the faint end of the luminosity function ($M_B \gtrsim -16$). On the other hand, our simulations aim at describing in a self–consistent way the hydrodynamical response of the ICM to star formation, stellar feedback and chemical enrichment.

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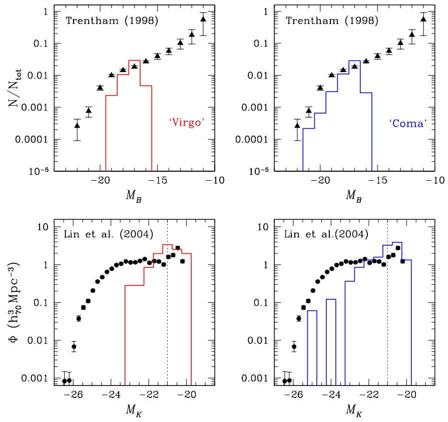

Fig. 1. *Top panels*: B–band luminosity functions at z=0 for the standard (AY-SW) "Virgo" (*left*) and "Coma" (*right*) simulations; the LFs are normalized to have the same number of galaxies as the observed average LF (Trentham 1998, *triangles*) within the populated luminosity range ($-19 \leq M_B \leq -17$). *Bottom panels*: K–band LFs for the same clusters, compared to the observed average LF by Lin *et al.* (2004); the dotted line marks the limit $M_K \leq -21$ where the observational estimate is considered reliable.

Our cosmological N-body simulation has been performed using the FLY code (Antonuccio *et al.*, 2003) on a standard ΛCDM model The selected clusters and groups isolated from the cosmological simulation, as identified at $z = 0$, have been resampled and resimulated (adding the baryon particles according to a $f_b = 0.12$) by means of an improved version of the Tree-SPH code described in Sommer-Larsen, Götz & Portinari (2003; SLGP). The mass resolution reached inside the resampled lagrangian subvolumes from the cosmological set was such that $m_{DM} = 1.8 \cdot 10^9 h^{-1} M_\odot$ and $m_g = m_* = 2.5 \cdot 10^8 h^{-1} M_\odot$.

The results hereby presented refer to the two largest systems: "sub-Coma" ($M_{vir} = 12.4 \cdot 10^{14} M_\odot$, $< kT_{ew} > \simeq 6$ keV) and "Virgo" ($2.8 \cdot 10^{14} M_\odot$, 3 keV).

The adopted TreeSPH code schematically includes the following features: conservative solution of entropy equation; metal-depending atomic radiative cooling; star formation, according to either an Arimoto-Yoshii (AY) or a Salpeter IMF; feedback as starburst (SN II) driven galactic winds; chemical evolution with non-instantaneous recycling of gas and heavy elements (H, He, C, N, O, Mg, Si, S, Ca, Fe); thermal conduction; meta-galactic, redshift-dependent UV field. All the runs implement the "Super-Wind" (SW) scheme, characterized by high efficiency parameters ϵ_{SF} and f_{wind}: the latter is amplified by a factor 2 or 4 in those runs simulating the effect of stronger non-stellar feedback (AGN). On the top of this model, it has been added either thermal conduction (at $\frac{1}{3}$ Spitzer value (COND runs), or pre-heating in form of 0.75/1.50/50cm^2 keV injected per particle at z=0 (PH runs). Finally, we ran as a test the WFB simulation, which adopts a normal feedback scheme with only early winds at low values of f_{wind} (as described in SLGP), and the ADIABATIC run without cooling nor star formation at all.

2. Results on cluster galaxies

2.1. Luminosity Functions

Each star particle represents a Single Stellar Population (SSP), with individual stellar masses distributed according to a particular IMF. We keep record of the age and the metallicity of each of these SSPs and hence the global luminosities and colours of the member galaxies are computed. We identify for the standard (SW-AY) runs 42 galaxies in "Virgo" and 212 galaxies in "Coma".

In Fig. 1 we compare the B–band and K–band luminosity function (LF) of our simulated cluster galaxies, exluding the cD, to two observational composite LFs. The number of resolved individual galaxies quickly drops for objects fainter than $M_B \sim$ -17, both in "Virgo" and in "Coma", due to the resolution limits. Although we are missing the dwarf galaxies that largely dominate in number, we are able to describe the bulk of the stellar mass and of the luminosity in clusters, which is dominated

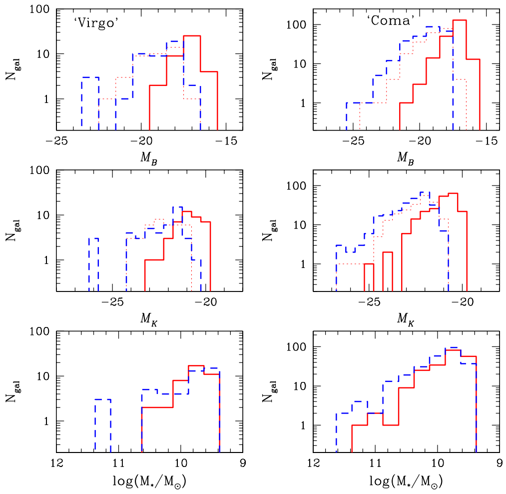

Fig. 2. *Top panels:* Luminosity functions in absolute number of galaxies per *B*-band magnitude bin for the standard (AY-SW) "Virgo" and "Coma" simulations, at $z = 0$ (*solid lines*) and $z = 1$ (*dashed lines*); the dotted lines represents the expected $z = 1$ LF if pure passive evolution of the stellar populations is applied to the $z = 0$ LF. *Middle panels:* Same, for the K-band luminosity functions. *Bottom panels:* Mass function of cluster galaxies at $z = 0$ and $z = 1$.

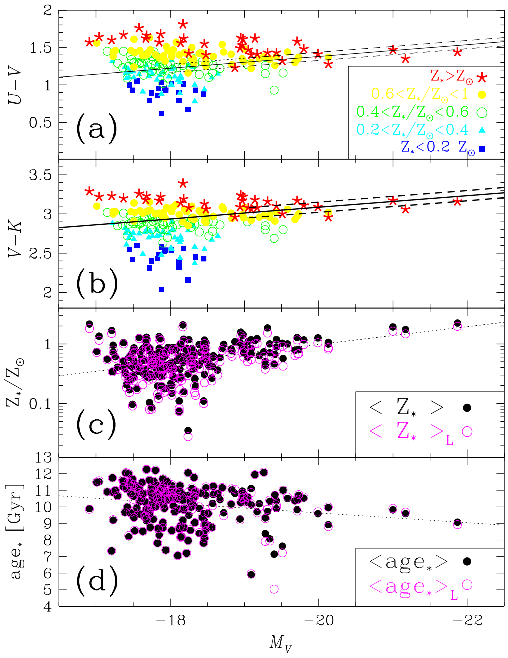

Fig. 3. (a–b) Colour–magnitude relation at z=0 for galaxies in the simulated "Coma" cluster, compared to the observed relation with its scatter (*solid* and *dashed* lines, from Bower *et al.* 1992; *dotted* lines, from Terlevich *et al.* 2001). The extension of the dashed/dotted lines indicates the magnitude range actually probed observationally, while the solid line is an extrapolation of their fit to lower magnitudes. **(c)** Metallicity–luminosity relation for the "Coma" galaxies (full symbols for mass–averaged stellar metallicity, open symbols for luminosity–weighted metallicity); the dotted line is a linear fit. **(d)**: Age–luminosity relation for the "Coma" galaxies (mass–average and luminosity–weighted stellar ages); the dotted line is a linear fit.

by galaxies around L_*. In the significative magnitude range, the shape of the predicted and observed LF is directly comparable. Yet, the simulated LF is steeper than the observed one, namely we underestimate the relative number of bright galaxies, at least within the SW model here shown. We have found that increasing the feedback strength results in decreasing the masses of all galaxies, and hence, in particular, the number of bright galaxies. Alongside this, the LF in the Salpeter cases is broader in luminosity, due the lower stellar feedback with respect to the AY IMF, allowing a larger accumulation of stellar mass in galaxies.

The LF in clusters can evolve due to two effects: passive luminosity evolution from the aging of the stellar populations in the galaxies, and mass evolution due to dynamical effects such as mergers, tidal stripping and dynamical friction. In Fig. 2 we show the evolution of the B and K band LFs of our "Virgo" and "Coma" clusters. The $z = 1$ LF is shifted to brighter magnitudes with respect to the distribution at $z = 0$. Both passive luminosity evolution and dynamical mass evolution are seen to play a role. In particular, since the bulk of the stars in our galaxies are formed at $z \gtrsim 2$ (see Fig. 3,

bottom panel), luminosity dimming is an important effect.
The LF inferred at $z = 1$ as expected from pure passive evolution of the $z = 0$ LF (dotted line in Fig. 2) matches very closely the actual LF in the $z = 1$ frame. This indicates that luminosity dimming of the stellar populations drives most of the LF evolution and the fading to fainter magnitudes from $z = 1$ to $z = 0$ for the simulated galaxy population. In the brightest luminosity bins of our LF, some additional, dynamical effect seems to be required. To assess mass evolution effects, we plot in the lower panels of Fig. 2 the mass function of cluster galaxies at $z = 1$ and at $z = 0$, which appear indeed very similar. "Over–merging" onto the central cD in cosmological simulations can be responsible for depleting the number of galaxies at the bright end of the LF: yet the results of a test simulation at 8 times higher mass and two times better force resolution we performed do allow us to disregard this interpretation.

2.2. The Red Sequence

The light and stellar mass in clusters of galaxies is dominated by bright, massive ellipticals, which are known to form a tight colour-magnitude relation, or Red Sequence. In Fig. 3ab, we compare the colour–magnitude relation for our "Coma" cluster galaxies, excluding the cD, to two observed Red Sequences of Coma. There is overall agreement, although our Red Sequence is not as extended as the observed one, and it also The colour–magnitude relation is classically interpreted as a mass–metallicity relation. In our simulations, the bulk of the stars in the simulated galaxies are formed at $z \gtrsim 2$, hence our galaxies are essentially coeval (9-10 Gyr old: Fig. 3d) and their colour–magnitude relation is mostly a metallicity effect, as it can be seen from combining these results with the metallicity–luminosity relation displayed in Fig. 3c. Although metal-rich objects seem to exist at all luminosities, the fraction of metal–poor galaxies (as well as the scatter in metallicity) increases with decreasing galaxy luminosity; the average stellar metallicity decreases for fainter galaxies (dotted line), which ultimately drives the simulated colour–magnitude relation.

All in all, the simulated Red Sequence appears to be a robust prediction of our simulations, quite unaffected by the adopted physical prescriptions other than the chosen IMF.

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