Properties of intra-group stars and galaxies in galaxy groups: ‘normal’ versus ‘fossil’ groups

Jesper Sommer-Larsen

Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark

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ABSTRACT
Cosmological [cold dark matter (ΛCDM)] TreeSPH simulations of the formation and evolution of 12 galaxy groups of virial mass ∼10^{14} M_☉ have been performed. The simulations invoke star formation, chemical evolution with non-instantaneous recycling, metallicity-dependent radiative cooling, strong star-burst driven galactic super-winds and effects of a meta-galactic ultraviolet (UV) field. The intra-group (IG) stars are found to contribute 12–45 per cent of the total group B-band luminosity at z = 0. The lowest fractions are found for groups with only a small difference between the R-band magnitudes of the first and second ranked group galaxy (∆m_{12,R} ∼ 0.5), the larger fractions are typical of ‘fossil’ groups (FGs, ∆m_{12,R} ≥ 2). A similar conclusion is obtained from BVRIJK surface brightness profiles of the IG star populations. The IG stars in the four FGs are found to be older than the ones in the eight ‘normal’ groups (non-FGs), on average by about 0.3–0.5 Gyr. The typical colour of the IG stellar population is B − R = 1.4–1.5, for both types of systems in good agreement with observations. The mean iron abundance of the IG stars is slightly sub-solar in the central part of the groups (r ∼ 100 kpc) decreasing to about 40 per cent solar at about half the virial radius. The IG stars are α-element enhanced with a trend of [O/Fe] increasing with r and an overall [O/Fe] ∼ 0.45 dex, indicative of dominant enrichment from Type II supernovae. The abundance properties are similar for both types of systems. The velocity distributions of the IG stars are, at r ∼ 30 kpc, significantly more radially anisotropic for FGs than for the non-FGs; this also holds for the velocity distributions of the group galaxies. This indicates that an important characteristic determining whether a group becomes fossil or not, apart from its formation time, as discussed by D’Onghia et al., is the ‘initial’ velocity distribution of the group galaxies. For FGs, one can dynamically infer the (dark matter dominated) mass distribution of the groups all the way to the virial radius, from the kinematics of the IG stars or group galaxies. For the non-FGs, this method overestimates the group mass at r ≥ 200 kpc, by up to a factor of 2 at the virial radius. This is interpreted as FGs being, in general, more relaxed than non-FGs. Finally, FGs of the above virial mass should host ∼500 planetary nebulae at projected distances between 100 and 1000 kpc from the first ranked galaxy. All results obtained appear consistent with the tidal stripping and merging scenario for the formation of FGs, put forward by D’Onghia et al.

Key words: cosmology: theory – galaxies: evolution – galaxies: formation.

1 INTRODUCTION
Hierarchical structure formation theories predict that the field star populations of haloes of galaxies like the Milky Way should consist partly of stars originally born in small proto-galaxies and later tidally stripped from these by the main galaxy or through interaction with other proto-galaxies. The halo stars resulting from tidal stripping or disruption of a proto-galaxy will stay localized in phase-space for a long period, and several such ‘streams’ of halo stars have been detected in the haloes of the Milky Way and M31 (e.g. Helmi et al. 1999; Ferguson et al. 2002).

From the point of view of structure formation, galaxy groups or clusters can be seen as scaled up versions of galaxies in hierarchical scenarios. In particular, tidal gravity fields will strip/disrupt galaxies in the group or cluster in a similar way as satellite galaxies in galaxy haloes, and a population of intra-group (IG) or intra-cluster (IC) stars should thus at present reside between the group and cluster galaxies.

*E-mail: jslarsen@tac.dk

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It has been known for decades that cD galaxies are embedded in extended envelopes presumed to consist of stars tidally stripped off galaxies in the process of being engulfed by the cD (e.g. Oemler 1976; Dressler 1979). In recent years, it has been possible to perform quantitative studies of these stellar envelopes through ultra-deep surface photometry of the general stellar population (e.g. Gonzalez et al. 2000; Feldmeier et al. 2002, 2004a; Gonzalez, Zabludoff & Zaritsky 2005; Mihos et al. 2005), or imaging/spectroscopy of individual planetary nebulae (PNe) (e.g. Arnaboldi et al. 2002, 2003; Feldmeier et al. 2004b) or supernovae Type Ia (Gal-Yam et al. 2003). The potential importance of IC stars in relation to the chemical enrichment of the intra-cluster medium (ICM) was recently discussed by Zaritsky, Gonzalez & Zabludoff (2004) and Lin & Mohr (2004).

Napolitano et al. (2003) have used an N-body dark matter (DM) only fully cosmological simulation of the formation of a Virgo-like cluster to make predictions about IC stars. They find that unrelated velocity distributions and (bulk) streaming motions of the IC stars should be common due to the large dynamical time-scales in clusters. The DM only simulations have been complemented by various N-body simulations which invoke a more realistic modelling of the stellar properties of galaxies in order to study their fate in a cluster environment. In relation to the properties of the IC stars, recent progress has been made by Dubinski, Koranyi & Geller (2003) and Feldmeier et al. (2004a).

In general, the properties of the system of IC stars are set by two main effects: (i) the cool-out of gas and subsequent conversion of cold, high-density gas to stars in individual galaxies and (ii) the stripping/disruption of the galaxies through interactions with other galaxies and the main cluster potential. Since such interactions will generally affect the star formation rate (as long as a reservoir of gas is available), the former process is intimately coupled to the latter. Only fairly recently has it been possible to carry out fully cosmological gas-dynamical/N-body simulations of the formation and evolution of galaxy clusters at a sufficient level of numerical resolution and physical sophistication that the cool-out of gas, star formation, chemical evolution and gas inflows and outflows related to individual cluster galaxies can be modelled to, at least, some degree of realism (e.g. Valdarnini 2003; Tornatore et al. 2004; Romeo, Portinari & Sommer-Larsen 2005a; Romeo et al. 2005b), though the problem of excessive, late time central cooling flows remains. Recently, such simulations have been analysed with emphasis on the properties of the IC stars (Murante et al. 2004; Willman et al. 2004; Sommer-Larsen, Romeo & Portinari 2005, hereafter SLRP05). Main observed properties of the IC light, such as the global IC light fractions of ∼20 per cent (e.g. Arnaboldi 2004), and the patchy distribution of IC light can be reproduced, giving such simulations some credibility, also in relation to modelling the stripping and disruption of galaxies in the cluster environment.

Work on IG light (IGL)/stars is much more in its infancy. Using PNe, Castro-Rodriguez et al. (2003) and Feldmeier et al. (2004c) estimate IGL fractions of just a few per cent for the Leo and M81 groups, respectively. On the other hand, Da Rocha & Mendes de Oliveira (2005) find a large range, 0–46 per cent, from broadband imaging of three compact groups, and for yet another Hickson Compact Group White et al. (2003) found an IGL fraction of 38–48 per cent. Gonzales and collaborators find that the combined luminosity of the brightest galaxy and the IC/IG light is about 40–60 per cent of the total for both groups and clusters. The above authors all study ‘normal’ groups, as opposed to the fairly recently discovered class dubbed ‘fossil’ groups (FGs), first discovered using the ROSAT X-ray satellite by Ponman et al. (1994). FGs are characterized by a bright central galaxy (BG1), and a gap in the R-band luminosity function of at least two magnitudes, to the second brightest galaxy (BG2), and have been detected up to a redshift of at least 0.6 (Ulmer et al. 2005).

This paper represents the first detailed theoretical study of the IGL/stars, based on fully cosmological gas-dynamical/N-body simulations. The paper builds on the work of D’Onghia et al. (2005), who performed high-resolution simulations of a sample of 12 (fairly massive) groups of virial mass ∼10^{14} M_{⊙} and virial (X-ray) temperature ∼1.5 keV. The groups were selected essentially randomly, from a large cosmological simulation. D’Onghia et al. interpret the FG phenomenon in terms of the hierarchical structure formation scenario, such that FGs are groups which assemble their DM haloes earlier than ‘normal’ groups. This leaves sufficient time to cause (second ranked) L ∼ L_{⋆} galaxies, initially orbiting in the groups, to reach the central parts due to dynamical friction, (mainly) against the DM. During this, the galaxies are tidally stripped, and finally disrupted and engulfed by the BG1. One would hence expect that the IGL/star fraction in FGs would be somewhat larger than in non-fossil groups (non-FGs).

Here, the properties of the IGL/stars and group galaxies are discussed on the basis of the simulations described above, with particular emphasis on comparing FGs to non-FGs. Results on IG star/group galaxy formation epochs, multi-band surface brightness profiles, colours, abundances, kinematics and dynamics are presented.

Section 2 briefly describes the code and the numerical simulations; in Section 3 the results obtained are presented and discussed; and finally Section 4 constitutes the conclusions.

2 THE CODE AND SIMULATIONS

Simulations of 12 galaxy group-sized DM haloes in the low-density, flat cold dark matter (ΛCDM) scenario with ΩM = 0.3, ΩΛ = 0.7, h = H₀/100 km s⁻¹ Mpc⁻¹ = 0.7 and σ8 = 0.9 were performed using the TreeSPH code briefly described in SLRP05. The code incorporates the ‘conservative’ entropy equation solving scheme of Springel & Hernquist (2002); chemical evolution with non-instantaneous recycling of gas and heavy elements tracing 10 elements (H, He, C, N, O, Mg, Si, S, Ca and Fe; Lia, Portinari & Carraro 2002a,b); atomic radiative cooling depending on gas metal abundance and a redshift-dependent, meta-galactic UV field; continuing, strong galactic winds driven by star-bursts (SNII), optionally enhanced to mimic active galactic nucleus (AGN) feedback; and finally thermal conduction. A fraction f_W of the energy released by SNII explosions goes initially into the interstellar medium (ISM) as thermal energy, and gas cooling is locally halted to reproduce the adiabatic super-shell expansion phase; a fraction of the supplied energy is subsequently (by the hydro code) converted into kinetic energy of the resulting expanding super-winds and/or shells.

The original DM-only cosmological simulation, from which the groups have been drawn and re-simulated at higher mass and force resolution, was run with the code FLY (Antonuccio-Delogu, Becciani & Ferro 2003) for a cosmological box of 150 h⁻¹ Mpc box-length. When re-simulating with the hydro-code, baryonic particles were ‘added’ adopting a global baryon fraction of f_B = 0.12. The mass resolution was increased by up to 2048 times, and the force resolution by up to 13 times (see below). The initial redshift for the cosmological run, as well as for the group re-simulations, was z_i = 39.
12 groups were randomly selected for re-simulation. The only selection criterion was that the groups should have virial masses close to (within 10 per cent) $1 \times 10^{14} \, M_\odot$, where the virial mass is the mass at $z = 0$ inside the virial radius, defined as the region for which the average mass density is 337 times the average of the Universe (e.g. Bryan & Norman 1998). The corresponding virial radius is about 1.2 Mpc, and the virial (X-ray) temperature is about 1.5 keV. The purpose of this project was to study a cosmologically representative sample of groups, so no prior information about merging histories was used in the selection of the 12 groups.

Particle numbers were about 250-300 000 smoothed particle hydrodynamics (SPH)+DM particles at the beginning of the simulations increasing to 300-350 000 SPH+DM+star particles at the end. A novelty was that each star-forming SPH particle of the initial mass is gradually turned into a total of eight star particles. This considerably improves the resolution of the stellar component. SPH particles, which have been formed by recycling of star particles, will have an eight of the original SPH particle mass – if such SPH particles are formed into stars, only one star particle is created. As a result, the simulations at the end contain star particles of mass $m_\ast = 3.1 \times 10^7 \, h^{-1} \, M_\odot$, SPH particles of masses $m_{\text{gas}} = 3.1 \times 10^7$ and $2.5 \times 10^7 \, h^{-1} \, M_\odot$, and DM particles of $m_{\text{DM}} = 1.8 \times 10^8 \, h^{-1} \, M_\odot$. Gravitational (spline) softening lengths of 1.2, 1.2, 2.5 and 4.8 $h^{-1}$ kpc, respectively, were adopted.

To test for numerical resolution effects, one of the 12 groups (a ‘fossil’ group) was in addition simulated at eight times (four for star particles) higher mass and two times (1.6 for star particles) higher force resolution, than the ‘standard’ simulations, yielding star particle masses $m_\ast = 7.8 \times 10^6 \, h^{-1} \, M_\odot$, SPH particle masses $m_{\text{gas}} = 7.8 \times 10^7$ and $3.1 \times 10^7 \, h^{-1} \, M_\odot$, DM particle masses $m_{\text{DM}} = 2.3 \times 10^8 \, h^{-1} \, M_\odot$, and gravitational (spline) softening lengths of 0.76, 0.76, 1.2 and 2.4 $h^{-1}$ kpc, respectively. For this simulation, particle numbers are about 1 400 000 SPH+DM particles at the beginning of the simulation increasing to 1 600 000 SPH+DM+star particles at the end.

In previous simulations of galaxy clusters (Romeo et al. 2005a,b; SLRP05), it was found that in order to get a sufficiently high ICM abundance a combination of a large value of $f_w$ and a fairly top-heavy initial mass function (IMF) has to be employed. For the present simulations, we used the ‘standard’ parameters described in the above works: $f_w = 0.8$, an IMF of the Arimoto–Yoshii type and zero conductivity. The existence of narrow ‘cold fronts’, observed in the many clusters, indicates that thermal conduction is generally strongly suppressed in the ICM. Moreover, it has previously been found that runs with a conductivity of 1/3 of the Spitzer value, and runs with zero conductivity, yield very similar results for the stellar components (Romeo et al. 2005a).

3 RESULTS AND DISCUSSION

This section presents results for the 12 groups, at $z = 0$, mainly run at ‘standard’ numerical resolution.

A well-known problem in the modelling of galaxy groups and clusters is the development of late-time cooling flows with bases at the position of BG1 and associated central star formation rates, which are too large compared to observations. In calculating the optical properties of the group galaxies, a crude correction for this is made by removing all stars formed at the base of the cooling flow since redshifts $z_{\text{corr}} = 2$ or 1. Both redshifts correspond to times well after the bulk of the group stars have formed. The correction amounts to 20–40 per cent in terms of numbers of BG1 stars. Using $z_{\text{corr}} = 2$ or 1 results in minor differences, so $z_{\text{corr}} = 2$ is adopted in this paper [for further discussion of this point see Sommer-Larsen et al. (2005)]. In cases where a similar correction of BG2 is appropriate (typically for non-FGs, where BG2 enters into the main DM halo fairly late, $z \lesssim 0.5$), BG2 is corrected as well. These corrections are quite minor, $\lesssim 10$ per cent in terms of numbers of stars (D’Onghia et al. 2005).

At $z = 0$, $1.7 \times 10^3 - 2.9 \times 10^4$ star particles are located inside of $r_{\text{vir}} \simeq 1200$ kpc (to within $\pm 3$ per cent) in the 12 groups simulated at standard resolution, and $9.3 \times 10^3$ star particles are located inside of $r_{\text{vir}}$ of the FG simulated at high resolution. The corresponding masses in star particles are $5.3 \times 10^{11}-9.0 \times 10^{11} \, h^{-1} \, M_\odot$ or a fraction of about 1 per cent of the total virial mass. In the following, star particles will be referred to simply as ‘stars’. The calculation of stellar luminosities is briefly described in Section 3.2.

Eight of the groups are characterized by an $R$-band magnitude difference $\Delta m_{12,R}$ between the brightest (BG1) and second brightest (BG2) galaxy of less than 2 – following D’Onghia et al. (2005) these are classified as ‘normal’ or non-FGs. Four have a magnitude difference $\Delta m_{12,R} \gtrsim 2$ – these are classified as ‘fossil’ groups (FGs).

The effective radii of the BG1s, calculated from the $b$-band surface brightness profiles, are $r_{\text{eff}} \simeq 10-15$ kpc, taking the inner 50 kpc of the groups as the extent of the BG1s – see below. The $b$-band absolute magnitudes of the BG1s lie in the range from $-20.5$ to $-22.5$. Compared to observations, $M_b \sim -21$ corresponds to the brighter end of the luminosity function of ordinary groups (Khosroshahi et al. 2004), whereas $M_b \sim -22.5$ corresponds to typical values for BG1s in FGs (Jones et al. 2003). Moreover, from Kormendy (1977) it follows that an elliptical galaxy of $M_b \sim -21.5$ should have an $R_{\text{eff}} \sim 10$ kpc, with a scatter of about a factor of 2, in agreement with the above findings.

3.1 Identifying group galaxies and IG stars

Group galaxies were identified using the algorithm described in detail in SLRP05: a cubic grid of cube-length $\Delta l = 20$ kpc was overlaid the group, and all cubes containing at least $N_{\text{bg}} = 10$ stars are identified. Subsequently, each selected cube is embedded in a larger cube of cube-length $3\Delta l$. If this larger cube contains at least $N_{\text{min}} = 15$ star particles, which are gravitationally bound by its content of gas, stars and DM, the system is identified as a potential galaxy. Since the method can return several, almost identical versions of the same galaxy, only the one containing the largest number of star particles is kept and classified as a galaxy. The galaxy (stellar) mass resolution limit is about $5 \times 10^8 \, h^{-1} \, M_\odot$ for the normal-resolution runs, and $6 \times 10^7 \, h^{-1} \, M_\odot$ for the high-resolution run.

For the FGs, an average of 12 galaxies (including the BG1) are found inside the virial radius to the resolution limit of $M_b \sim -18.5$. For the non-FGs, the corresponding number is 14. For the high-resolution run of a FG, 70 galaxies are identified to the resolution limit $M_b \sim -16.5$.

There are no galaxies closer than $r_{\text{BG1}} = 50$ kpc to the BG1 in either of the 12 $z = 0$ frames (this is not true in all $z \sim 0$ frames, though, but it was tested that the results presented in the following did not depend on which $z \sim 0$ frame was chosen to represent the present epoch).

The system of IG stars is defined as the stars located at BG1 distances $r_{\text{BG1}} \leq r \leq r_{\text{vir}}$ and not inside of the tidal radius of any galaxy in the group. The tidal radius for each galaxy is taken to be the Jacobi limit

$$r_T = \left( \frac{m}{3M} \right)^{1/3} D, \quad (1)$$

where $m$ is the mass of stars, gas and DM in the galaxy (inside of $r_1$), $D$ is the distance from the BG1 to the galaxy and $M$ is the total mass of the group inside of $D$ (e.g. Binggeli et al. 1987). The BG1 itself is effectively just the inwards continuation of the system of IG stars, so the division between IG and BG1 stars is somewhat arbitrary (hence below IC star fractions for $r_{BG1} = 50$ as well as 100 kpc are quoted). The above definition of IG stars is conservative, since the tidal radii are calculated on the basis of the $z = 0$ frame BG1 distances of the galaxies. For any galaxy which has been through at least one peri-centre passage, this tidal radius should be taken as a firm upper limit. Moreover, some IG stars will be inside of the tidal radius of one of the group galaxies just by chance. As the total ‘tidal volume’ of all the group galaxies is found to be on average less than 10 per cent of the group virial volume, this effect can be neglected to a good first approximation.

3.2 The IGL fraction

For comparison with observations, it is relevant to determine stellar luminosity fractions, rather than mass fractions. Since ages and metallicities are available for all star particles, the photometric properties are straightforward to calculate treating each star particle as a single Stellar Population (SSP; see Romeo et al. 2005a for details). SSP luminosities are computed by mass-weighted integration of the Padova isochrones (Girardi et al. 2002), according to the Arimoto–Yoshii IMF. For $r_{BG1} = 50$ kpc, it is found that the IG stars contribute 20–45 per cent of the group $B$-band luminosities, with the lower value typical for non-FGs with small $\Delta m_{12-14}$, and the larger for FGs (adopting instead $r_{BG1} = 100$ kpc, the IGL fractions decrease to 0.12–0.25). These IGL fractions are typical of what is found observationally for galaxy clusters (e.g. Arnauld 2004). Only a few observational studies of IGL in groups are presently available, and they all refer to ‘normal’ groups (non-FGs). Estimates of the IGL fraction in such systems range from a few per cent (Leo Group; Castro-Rodriguez et al. 2003; M81 Group, Feldmeier et al. 2004c), 0.46 per cent (Hickson Compact Groups 79, 88 and 95; Da Rocha & Mendes de Oliveira 2005) to almost 50 per cent (HCG 90; White et al. 2003). Gonzalez and collaborators find for their sample of 26 clusters and groups, spanning a range of velocity dispersions of 200–1100 km s$^{-1}$, that the combined BG1+IGL amounts to 40–60 per cent of the total (Anthony Gonzales, private communication). Evidently, the system-to-system variation is very large, which is in line with the findings given in this paper (Section 3.3). Moreover, one expects the projected distribution of IGL to be patchy (Section 3.7), which adds to the observational scatter, as the fields surveyed usually do not cover the entire group.

3.3 Mean formation redshifts, surface brightness profiles and colours of the IG stars

Fig. 1 shows the mean (spherically averaged) redshift of formation, $z_f$, of the BG1 + IG stars and stars in galaxies (except the BG1) as a function of radial distance from the centre of the BG1 for the FGs (solid lines) and non-FGs (dashed lines), respectively. The results presented here and in the following have been averaged over the four FGs and eight non-FGs, respectively. For the FGs, the average formation redshift of the IG stars is $z_f \sim 2.75$ at $r \sim 100–200$ kpc, gradually decreasing to $z_f \sim 2.5$ at the virial radius. The IG stars in the non-FGs are on average somewhat younger (by about 0.2 in formation redshift). Qualitatively, this is to be expected, since FGs are found to assemble earlier than non-FGs (D’Onghia et al. 2005), such that merging and stripping processes take place earlier; and also, such that the decrease in star formation in the group galaxies in general, caused by ram-pressure stripping and other effects, (see below) takes place earlier.

The stars in galaxies (except the BG1) are on average somewhat younger than the IG stars (by about 0.2–0.4 in formation redshift) for both types of groups. This seems reasonable, since the bulk of the IG stars originates in (proto) galaxies, which have been partly or fully disrupted through tidal stripping in the main group potentials or by galaxy–galaxy interactions. In contrast, the galaxies still remaining at $z = 0$ have potentially been able to continue forming stars out of remaining cold gas or gas recycled by evolved stars and subsequently cooled to star-forming temperatures and densities. Still, due to ram-pressure stripping of the hot and dilute gas reservoir in galactic haloes and other effects, at least for cluster galaxies, the star formation rate decreases significantly from $z = 2$ to 0, considerably more so than in field galaxies (cf. Romeo et al. 2005a).

Comparing to the results for IC stars in two cluster simulations discussed by SLRP05, it is found that the IC stars are somewhat older on average (with $z_{IC} \sim 3$) than the IG stars. Again, this is to be expected, since clusters on average form from higher peaks in the initial cosmological fluctuations field, and hence experience ‘accelerated’ galaxy formation relative to groups.

In Fig. 2 is shown, for the four FGs and eight non-FGs, respectively, the median, azimuthally averaged $B_5 RI JK$ surface brightness profiles of the BG1+IG stars (projection is along the $z$-axis, defined in Section 3.5). The light profiles are approximately described by $r^{-1/4}$ laws. The slope flattens slightly beyond $R \sim 100$ kpc for both types of systems, at surface brightness levels of $V \sim 28$ mag arcsec$^{-2}$, corresponding to about the limit which can be reached by surface photometry (e.g. Feldmeier et al. 2002). The median surface brightness of the FG BG1+IG stars at $R \sim 10–250$ kpc is only about 20–45 per cent (0.2–0.4 mag) larger than that of the non-FG stars, but the variation in surface brightness between the individual non-FGs is quite large, about a factor of 5 ($\sim 1.7$ mag;
Figure 2. Azimuthally averaged multiband (BV RI JK going bottom up) surface brightness profiles of BG1+IG stars for the FGs (solid lines) and non-FGs (dashed lines).

Figure 3. Azimuthally averaged $B$-band surface brightness profiles of the eight individual non-FGs, shown by dot–dashed lines for systems with $\Delta m_{12,R} < 0.5$ mag, solid lines for $0.5 \leq \Delta m_{12,R} < 1$ mag and dashed lines for $1 \leq \Delta m_{12,R} < 2$ mag. The region shown on the x-axis corresponds to $39 < R < 150$ kpc.

Figure 4. Azimuthally averaged $B - V$ (solid lines), $B - R$ (dashed lines) and $I - K$ (dot–dashed lines) colours of the BG1+IG stars for the FGs (thick lines) and non-FGs (thinner lines), respectively.

Figure 5. Spherically averaged iron abundance profile of BG1+IG stars (solid lines) and stars in group galaxies (dashed lines), shown for FGs by thick lines and non-FGs by thin lines, respectively (results for $r < 20$ kpc are not shown for clarity).
observations of an IC field in the Virgo cluster (which has a virial mass of only two to three times that of the groups considered here) at an average projected distance of 150 kpc from M87 (which for the purposes here can be assumed coincident with cluster centre). They confirm an excess of red number counts, which they interpret as IC red giant branch (RGB) stars. By comparison with observations of a dwarf irregular, they conclude that these stars have $-0.8 < [\text{Fe/H}] < -0.2$, in quite good agreement with the results presented above.

Fig. 6 shows the corresponding oxygen-to-iron ratios as a function of $r$. Again, the results for FGs and non-FGs are quite similar. $[\text{O}/\text{Fe}]$ is super-solar everywhere for BG1+IG stars as well as galaxies, for the former being about 0.2 dex higher than for the latter. Both values lie in the range of present estimates for luminous elliptical galaxies in clusters. For IG/IC stars, no observational information is currently available (Arnaboldi, private communication).

For pure Type II supernovae enrichment and with the Arimoto–Yoshii IMF, one expects $[\text{O}/\text{Fe}]_{\text{SNII}} = 0.55$ (e.g. Lia et al. 2002a), so it follows from Fig. 6 that SNe Ia do contribute somewhat to the enrichment of the BG1+IG stellar populations, and (not surprisingly) even more so for the stars still in galaxies at $z = 0$ [in fact for an Arimoto–Yoshii IMF the global ($t \rightarrow \infty$) value of the SNII+SNIa enrichment is $[\text{O}/\text{Fe}] = 0.18$].

The fact that iron abundances and oxygen-to-iron ratios are so similar in FGs and non-FGs for both IG stars and galaxies indicates that the evolution in the two types of systems is quite similar, except that the formation of the FGs is accelerated relative to the non-FGs (cf. Fig. 1 and D’Onghia et al. 2005). In particular, the balance between the time-scale for SNII relative to SNIa production of iron and the time-scale for tidal stripping of IG stars must be similar in the two types of systems.

### 3.5 Kinematics of the IG stars and group galaxies

Using observed velocities of PNe, it will ultimately be possible to kinematically ‘dissect’ the systems of BG1+IG stars in nearby galaxy groups, like it is starting to be done for clusters, such as Virgo (e.g. Arnaboldi 2004; Feldmeier et al. 2004b). It is hence of considerable interest to determine for our simulations the kinematic properties of the BG1+IG stars, and of the group galaxies, for comparison. To this end, the following approach is adopted: the individual groups are rotated in such a way that the minor axis of the BG1s at $z = 0$ becomes the ‘$z$-axis’ (but note that the galaxy groups as well as the BG1s are only slightly flattened at $z = 0$). The four FGs and eight non-FGs are then centred at the BG1s and superposed for kinematic analysis. For each BG1+IG star and each group galaxy, three perpendicular velocity components are determined: the radial component $v_r = v \cdot e_r$, where $e_r$ is the unit vector pointing radially away from the centre of the cluster, the perpendicular (tangential) component $v_\phi = v \cdot e_\phi$, where $e_\phi$ is the unit vector perpendicular to $e_r$ and aligned with the $x$-$y$ plane and the third (tangential) component $v_z = v \cdot e_z$, where $e_z$ is the unit vector $e_z = e_r \times e_\phi$. The mean rotation $v_\phi$ and velocity dispersions $\sigma_r$, $\sigma_\phi$ and $\sigma_z$ of BG1+IG stars and galaxies are calculated in spherical shells. As was found for the two simulated clusters analyzed by SLRP05, rotation is dynamically insignificant and will be ignored in the following analysis. Fig. 7 shows the velocity dispersions of the BG1+IG stars as a function of radius for the FGs and non-FGs, respectively. As can be seen, the two tangential velocity dispersion are at all radii quite similar, confirming that the groups are only slightly flattened (alternatively the minor axis of the individual groups was oriented using the flattening of the entire groups, not just the BG1 – the groups were then again superposed, as above, this led to results very similar to what is presented here). Secondly, except for the central region ($r \lesssim 30$ kpc) the velocity distributions are clearly radially anisotropic. This is quantified in Fig. 8, which shows the radial dependence of the anisotropy parameter $\beta' = (\sigma_\phi^2 + \sigma_z^2)/2\sigma_r^2$, where $\beta'$ is the ratio of the kinetic energy in mean tangential (1D) and radial motions, respectively (for an isotropic velocity distribution $\beta' = 1$). In addition, it follows from the figure that the velocity distribution of the IG stars in the FGs is significantly more radially anisotropic than in the non-FGs. This is an important result in relation to understanding the FG phenomenon. D’Onghia et al. (2005) showed that the epoch of formation of a group is closely related to the ‘fossilness’ of a group. The present result indicates that a second parameter may

![Figure 6](https://academic.oup.com/mnras/article-abstract/369/2/958/3101600/958-968)

![Figure 7](https://academic.oup.com/mnras/article-abstract/369/2/958/3101600/958-968)
Figure 8. Velocity anisotropy parameter $\beta' = (\sigma_\phi^2 + \sigma_\theta^2)/2\sigma_r^2$ for BG1+IG stars for the FGs (circles) and non-FGs (squares). An isotropic velocity distribution has $\beta' = 1$.

be the anisotropy of the ‘initial’ velocity distribution of the group galaxies. The anisotropy of this distribution, as traced by the resulting IG stars at $z = 0$, appears to relate to the ‘fossilness’ of the group, in such a way that groups with highly radially anisotropic velocity distributions tend to become fossil. This seems quite reasonable in terms of a tidal stripping and merging scenario for the formation of FGs put forward by D’Onghia et al.

Fig. 9 shows the velocity dispersions of the group galaxies as a function of radius for the FGs and non-FGs, respectively. Given the fairly small numbers of galaxies in the superposed systems, 45 in the FGs and 105 in the non-FGs (inside of the virial radius), only $\sigma_r$ and $\sigma_t = \sqrt{(\sigma_\phi^2 + \sigma_\theta^2)/2}$ are shown. As was found by SLRP05, the velocity dispersions of the galaxies tend to be larger than for the IG stars. In particular, for the non-FGs $\sigma_t$ for galaxies is considerably larger than for IG stars. Moreover, within the considerable statistical uncertainties, the velocity distribution of the galaxies in the non-FGs is more isotropic than for the FGs, as was found for the IG stars. This again hints that velocity distributions are of importance in relation to the formation of FGs.

Observationally, for the BG1+IG stars one will only be able to determine line-of-sight velocities using PNe, not full 3D velocities. For direct comparison with observations shown in Fig. 10, for the FGs and non-FGs, respectively, are the projected velocity dispersions of the BG1+IG stars, and (for comparison) of the DM, versus projected distance from the BG1. The results shown have been obtained by averaging over rings projected along the $x$, $y$ and $z$ directions.

For the FGs, the projected stellar velocity dispersion is $\sim 400$ km s$^{-1}$ at the group centre, steadily decreasing to $\sim 200$ km s$^{-1}$ at the (projected) virial radius. For the non-FGs, which are less centrally concentrated, the projected stellar velocity dispersion is $\sim 300$ km s$^{-1}$ at the centre, increases to $\sim 400$ km s$^{-1}$ at $R \sim 400$ kpc and then decreases gradually with increasing $R$ to about 275 km s$^{-1}$ at projected $R_{\text{vir}}$.

The projected velocity dispersions of the DM follow a similar trend with $R$ as that of the stars, but are consistently larger. As the stars and DM are moving in the same gravitational potential, this implies that the density distribution of DM is flatter than that of the BG1+IG stars (SLRP05).

3.6 Dynamical determination of group mass distributions using IG stars and galaxies

It is of great interest to determine dynamical masses of groups and clusters, e.g. in relation to estimating the baryon fraction in such systems. The latter is of significant cosmological importance, as well as an important constraint which any successful model of group and cluster formation should meet. D’Onghia et al. (2005) showed that the DM haloes of FGs are assembled earlier than those of non-FGs. Given this, it seems reasonable to assume that FGs are dynamically more relaxed systems than non-FGs, and hence more suitable for...
the properties of the FG and non-FG galaxy populations. In particular, \( \sigma_\alpha(r) \) and \( \sigma_\beta(r) \) are known, rather than (from an observational viewpoint much more realistically) just the projected velocity dispersion. Moreover, assuming that \( n(r) \) is known, then equation (4) can be used to determine \( v_c(r) \) or equivalently the total mass distribution. If the system under consideration is relaxed, and the potential as well as the system close to spherical, one should approximately recover the true, underlying mass distribution in this way.

The above approach is now applied to the FGs and non-FGs, respectively. The result of this exercise is shown in Fig. 11. As can be seen, for the FGs both using IG stars and galaxies, one recovers the true mass distribution, expressed through \( v_c(r) \), quite well all the way to the virial radius, though the small number of galaxies in the FGs makes the mass determination using group galaxies somewhat uncertain. For the non-FGs, however, only in the inner (presumably most relaxed) parts of the groups, \( r \lesssim 200 \) kpc, one recovers the true mass distribution, whereas further out the above approach leads to an overestimate of the total mass. At the virial radius, this overestimate approaches a factor of 2. Also note that due to the larger number of galaxies in the non-FG template, the formal uncertainty on the mass estimate based on galaxies is smaller than for the FG case.

So it seems highly preferable to select FGs for purposes of observational baryon fraction estimation, mass estimation for comparison with gravitational lensing or X-ray estimated masses, etc. This appears to be a very useful result, given that the measurement of the difference in luminosity of the first and second ranked galaxy in a group is straightforward.

### 3.7 Predicted counts and distributions of IG PNe

In relation to upcoming searches for IG PNe, it is of interest to predict what may result from such undertakings. The expected number of PNe expected per solar \( B \)-band luminosity of the stellar population is \( \alpha_{1, B} = 9.4 \times 10^{-9} \) PNe / \( L_{B, \odot} \) \( \) (e.g. Arnaboldi et al. 2002; to be precise, this gives the number of PNe, within one \( B \)-band magnitude of the PNe luminosity function bright end cut). Based on these values, Fig. 12 shows the expected cumulative number of PNe within a ring of projected inner radius \( R \) and outer radius 1 Mpc for two systems: (i) the non-FG with the smallest projected \( B \)-band luminosity of the IG stars between 100 kpc and 1 Mpc, and (ii) the FG with the largest corresponding luminosity. As can be seen, the number count ratio is about a factor of 3. Even for the first group, a considerable number of PNe are expected to be found between 100 and 1000 kpc, about 200 PNe. However, two important points should be noted: first, the projected distribution of PNe is expected to be patchy. This is illustrated in Figs 13 and 14, which show the expected distributions of PNe projected along the \( z \)-axis for the two groups. In particular, for the non-FG, outside of about 100 kpc there are large coherent regions with no PNe at all. Secondly, the values of \( \alpha_{1, B} \) may vary by as much as a factor 5 (e.g. Castro-Rodriguez et al. 2003).

![Figure 11](https://example.com/figure11.png)

**Figure 11.** Equivalent circular speeds. Directly determined from the mass distributions of the FG and non-FG templates, using second part of equation (4): FGs and non-FGs are shown by thick solid and dashed lines not connecting symbols, respectively. Dynamically inferred from the kinematic and spatial properties of the systems of IG stars, using last part of equation (4): FGs and non-FGs are shown by solid and dashed lines connecting circles and triangles, respectively. Finally, shown by circles and triangles connected by dotted lines are the same quantities, but inferred instead from the properties of the FG and non-FG galaxy populations.

![Figure 12](https://example.com/figure12.png)

**Figure 12.** Cumulative number of PNe within a ring of projected inner radius \( R \) and outer radius 1 Mpc for two systems: (i) the non-FG with the smallest projected \( B \)-band luminosity of the IG stars between 100 kpc and 1 Mpc (dashed line) and (ii) the FG with the largest corresponding luminosity (solid line).
3.8 Numerical resolution

It is important to test whether the properties of the IG star and galaxy populations presented in this paper depend on the numerical resolution of the simulations. To this end, as mentioned in Section 2, one of the FGs was re-simulated at eight times higher mass and two times higher force resolution (4 and 1.6 times, respectively, for the star particles). This results in star particle masses $m_\star = 7.8 \times 10^6 \, h^{-1} \, M_\odot$, SPH particle masses $m_{\text{gas}} = 7.8 \times 10^6$ and $3.1 \times 10^7 \, h^{-1} \, M_\odot$, DM particle masses $m_{\text{DM}} = 2.3 \times 10^8 \, h^{-1} \, M_\odot$ and gravitational (spline) softening lengths of 0.76, 0.76, 1.2 and 2.4 $h^{-1} \, \text{kpc}$, respectively. Total particle numbers are about 1 400 000 SPH+DM particles at the beginning of the simulation increasing to 1 600 000 SPH+DM+star particles at the end.

In order to enable an optimal comparison between the normal- and high-resolution runs only Fourier modes up the Nyquist wavenumber of the normal-resolution simulation were used to prepare the initial conditions for the high-resolution run (i.e. additional high-wavenumber modes up to the Nyquist wavenumber of the high-resolution simulation were not added to the Fourier modes).

Fig. 15 shows the cumulative mass of BG1+IG stars and stars in galaxies outside of $r = 30 \, \text{kpc}$ for the normal- (thin lines) and high-resolution (thick lines) simulations of a FG, respectively. Runs at $z = 0$. There is good agreement between the runs – the somewhat larger mass in IG stars in the high-resolution simulation at $r \gtrsim 200 \, \text{kpc}$ is likely due to the better resolution of star-forming gas in the lower over-density regions which come to populate the outer parts of the group. The flattening of $M(<r)$ with increasing $r$ is due to the decrease in tidal stripping efficiency with $r$ (SLRP05).

Very good agreement between other quantities, such as velocity dispersions, galaxy luminosity functions, chemical properties, etc. is also found, as mentioned by D’Onghia et al. (2005). A detailed comparison will be presented in a forthcoming paper (D’Onghia et al., in preparation). Moreover, a high-resolution simulation of one of the non-FGs is also in progress.

4 CONCLUSIONS

This work discusses the $z = 0$ properties of the IGL/stars, as well as, mainly kinematic and dynamical properties of the group galaxies. The results are based on fully cosmological, $N$-body/hydrodynamical simulations of 12 galaxy groups. Physical processes treated include metal-dependent atomic radiative cooling, star formation, supernova-driven galactic super-winds, non-instantaneous chemical evolution and the effects of a meta-galactic, redshift-dependent UV field. In relation to modelling the properties of the IG stars, as well as galaxy groups in general, this is an important step forward with respect to previous theoretical works.

The main results obtained, in particular in relation to comparing FGs to non-FGs, are as follows.

The IG stars are found to contribute 12–45 per cent of the total group $B$-band luminosity at $z = 0$. This is in agreement with some estimates of the IGL fraction, but too large compared to other studies, partly based on PNe. The latter apparent disagreement might, however, be due to patchiness effects in the IGL as well as PNe distribution, as well as the intrinsic scatter in the $B$-band luminosity to PN number ratio (cf. Section 3.7).

The IG stars in the FGs form at a mean redshift $\bar{z}_f \sim 2.5–2.75$; in non-FGs the formation redshift is smaller by about 0.2. The stars in galaxies (excluding the BG1) form on average at redshifts 0.2–0.4 less than the IG stars, for both types of systems.
of this FG indicates that the results presented in this paper are largely robust to resolution changes.

In summary, all results obtained appear consistent with the tidal stripping and merging scenario for the formation of FGs, put forward by D’Onghia et al. In general, one should find more IGL and PNe in FGs, so observational projects to this end deserve to be promoted, also for testing the predictions made in this paper. In particular, for dynamical determination of group masses, for comparison with estimates based on gravitational lensing or X-ray emission, or for baryon fraction estimation, FGs seem considerably more useful than non-FGs.

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Properties of intra-group stars and galaxies