Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Galaxy formation modeling

Andrew J. Benson

Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, U.K. email: abenson@astro.ox.ac.uk

Abstract. Ab-initio modeling of galaxy formation is becoming ever more detailed and is including ever more physical processes in a bid to describe the process of galaxy formation more realistically. We will describe some recent advances and applications of the semi-analytic model of galaxy formation, GALFORM. In particular, we will describe a preliminary study of the effects of environment on galaxy morphology in a $z = 0.4$ cluster.

1. Galaxy formation modeling

Semi-analytic modeling of galaxy formation traditionally follows the birth and evolution of galaxies in the merging hierarchy of dark matter halos predicted to exist in cold dark matter (CDM) cosmologies. The merging hierarchy is computed from the extended Press-Schechter formalism (e.g. Lacey & Cole 1993) or from direct N-body simulations (Kauffmann et al. 1999, Helly et al. 2003a). Galaxy formation is then modeled by considering the rate at which gas can cool within these halos, the rate of galaxy merging (driven by dynamical friction) and the rate and efficiency of star formation and the associated feedback in individual galaxies (Cole et al. 2000). The accuracy of some of these ingredients has now been tested. For example, Fig. 1 shows a comparison of galaxy masses in the GALFORM model and a smoothed particle hydrodynamics calculation (Helly et al. 2003b), which demonstrates good agreement between these two approaches (see also Benson et al. 2001, Yoshida et al. 2002).

2. Recent results

2.1. *The galaxy luminosity function*

We have recently examined the ability of semi-analytic models to reproduce the luminosity function of galaxies (a key observable which all models must strive to reproduce). With only the traditional "reheating" feedback† usually employed in semi-analytic models it is impossible to simultaneously match the rather flat faint-end slope of the observed luminosity function and the very sharp cut-off at bright magnitudes. Fig. 2 shows two possible solutions to this problem. In the left-hand panel we allow thermal conductivity to transport energy into the gas residing in the central regions of galaxy groups and clusters, thereby reducing the rate of gas cooling and hence of galaxy formation. While this produces a good match to the luminosity function, an excessively high conductivity is required. The right-hand panel shows the effects of "superwinds" in which gas ejected from the galaxy by feedback is completely removed from the surrounding dark matter halo and is not allowed to participate in the galaxy formation process again. While superwinds are able to produce a reasonably good match to the luminosity function the

† With reheating feedback for every mass of stars formed in a galaxy a certain mass of cold gas is ejected from the galaxy into the surrounding halo. The amount of ejected gas depends on the depth of the potential well of the galaxy.

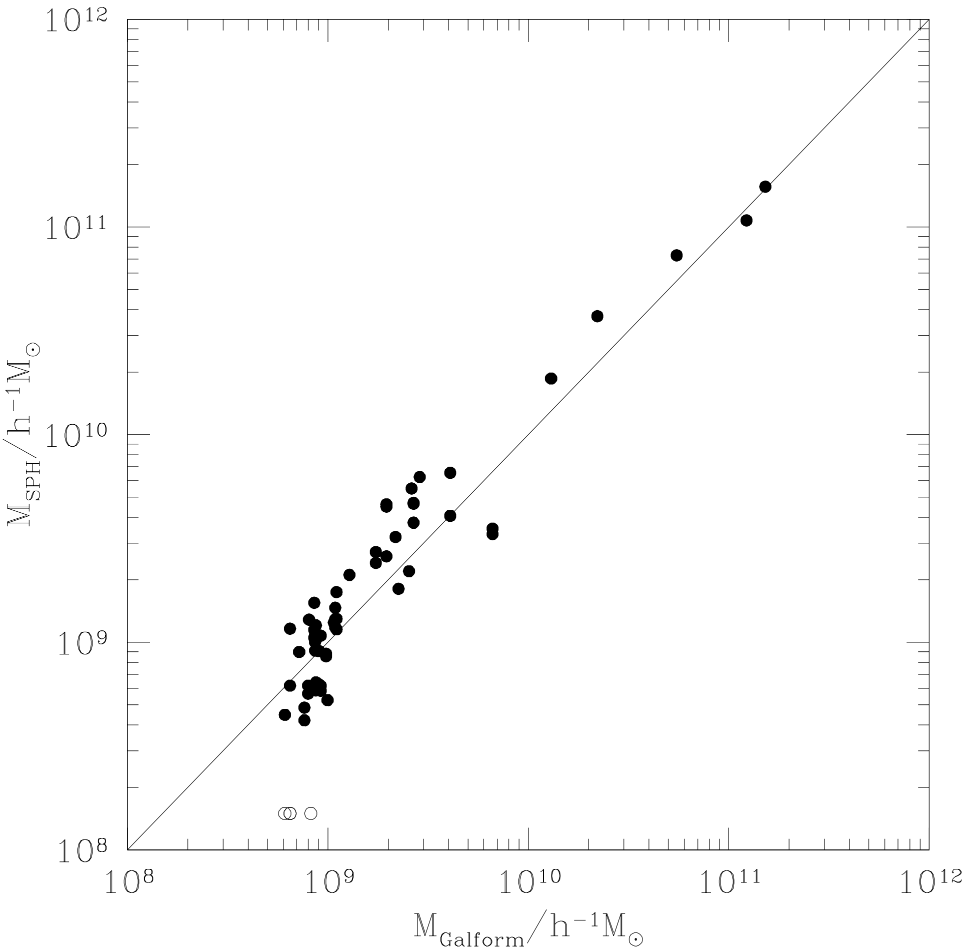

Figure 1. The correlation of galaxy masses as predicted by two different models of galaxy formation Helly et al. 2003b. Semi-analytic and SPH techniques were used to populate a dark matter halo with galaxies. Points show the masses of corresponding galaxies in the two simulations (i.e. those with similar spatial positions). Where no corresponding galaxy was found in the SPH simulation, an open point is plotted at an arbitrary position on the y-axis.

energy requirements are large—larger than is available from supernovae. This hints that perhaps a contribution of energy from AGN is required.

2.2. *Heating of galaxy disks*

Recently, we have developed a much more detailed model of satellite dark matter halo orbits and merging than has previously been possible within semi-analytic models. By tracking the orbit of each satellite halo, accounting for tidal mass loss and dynamical friction, we are able to determine the frequency with which satellite halos interact with the disks of galaxies such as the Milky Way and the consequences of those interactions. Figure 3 shows the initial distribution of orbital velocities for these satellite halos, measured at the time when they cross the virial radius of their host halo. This is used as input to a calculation of the amount of energy transferred from satellite halo orbits to galaxy disks. Figure 4 shows the resulting distribution of galaxy scale-heights (we plot

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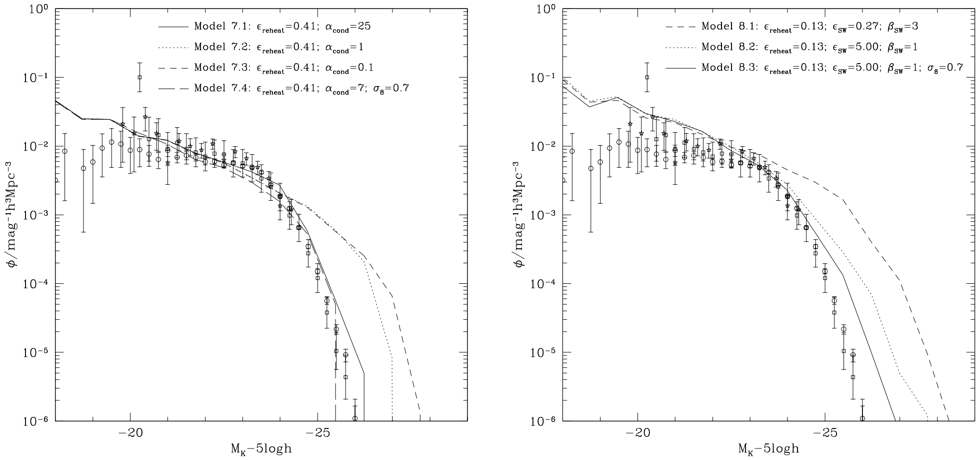

Figure 2. *Left-hand panel:* Lines show K-band luminosity functions predicted by the GALFORM model when the effects of thermal conduction on intra-cluster gas are considered. Model numbers correspond to the models of Benson et al. (2004). The parameter $\epsilon_{\rm reheat}$ specifies the amount of energy (in units of 10^{49} ergs) per solar mass of stars formed that is used to reheat gas from galaxy disks (i.e. to cause feedback), while $\alpha_{\rm cond}$ parametrizes the conductivity of the intracluster gas in units of the Spitzer conductivity. Observational data are taken from Cole et al. (2001) [circles], Kochanek et al. (2001) [squares] and Huang et al. (2002) [stars]. *Right-hand panel:* As left-hand panel except that results are shown for models with superwinds. The parameter $\epsilon_{\rm SW}$ quantifies the energy (in units of 10^{49} ergs) per solar mass of stars formed which is put into a superwind, while $\beta_{\rm SW}$ specifies the mass ejected into the superwind per solar mass of stars formed.

h, the ratio of vertical scale-height to radial scale-length) for a sample of galaxies. These are compared to a recent observational determination by Bizyaev & Mitronova (2002). The thickening of the disks predicted by our model is seen to be in good agreement with the data.

3. Role of environmental effects

The improved model of satellite galaxy orbits described above forms the backbone for a more detailed study of environmental effects than has previously been possible using semi-analytic techniques. As an example, Fig. 5 shows, in the left-hand panel, the projected positions of galaxies in a cluster at $z = 0.4$ with mass similar to that of Cl0024 as studied by Treu et al. (2003). The right-hand panel shows the cumulative mass function of dark matter halos associated with galaxies in the cluster, and demonstrates that the semi-analytic model of these halos reproduces the results of direct N-body calculations extremely well.

Using the positional information predicted by our model of galaxy orbits and the morphological information predicted by GALFORM for each model galaxy we can investigate how galaxy morphology depends upon environment. Fig. 6 shows the fractions of early and late-type galaxies as a function of distance from the cluster centre (left-hand panel) and as a function of local galaxy density (right-hand panel).

GALFORM predicts a strong trend of morphology with radius (namely that the early type fraction decreases towards smaller radii) within the cluster. Beyond about 0.3 Mpc the morphological mix reaches the field value and stays fairly constant. While this radial trend is seen in the real Cl0024, Treu et al. (2003) also demonstrate that morphology

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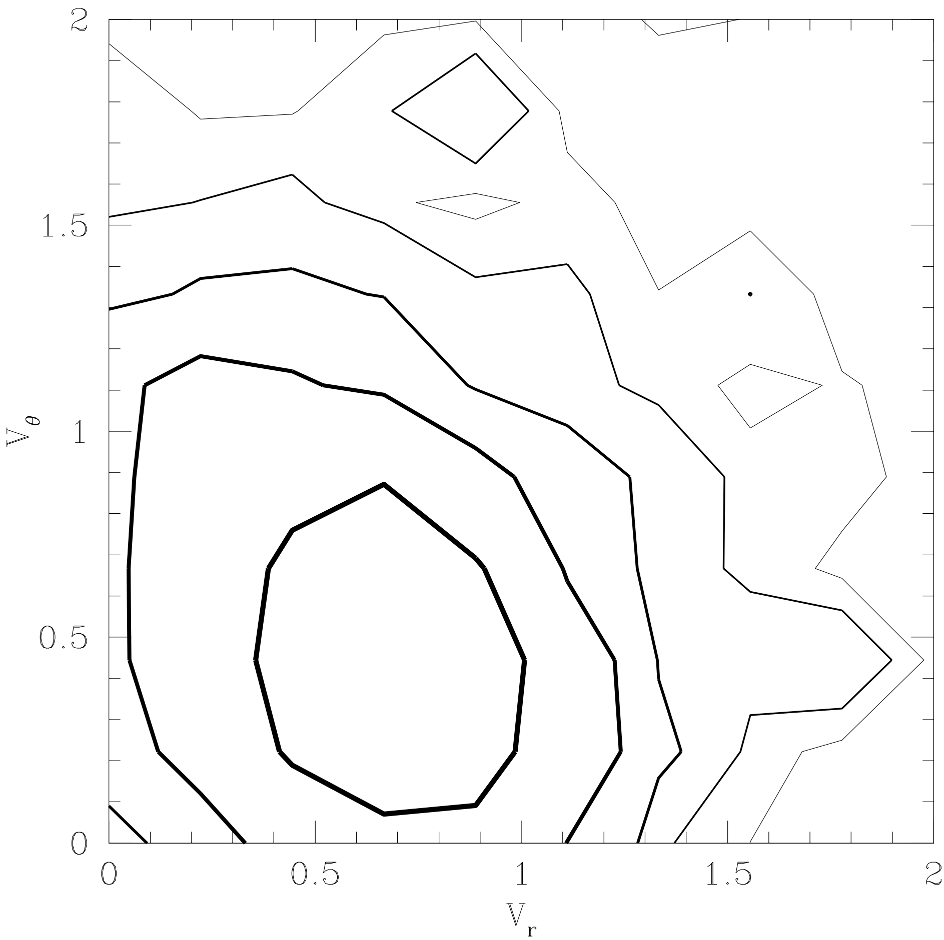

Figure 3. The distribution, $\mathrm{d}^2f/\mathrm{d}v_\mathrm{r}/\mathrm{d}v_\theta$, of radial and tangential velocities for merging dark matter halos. All velocities are expressed in units of the virial velocity of the more massive halo. Contours indicate the distribution measured from the VIRGO Consortium's ΛCDM GIF simulations. Contours are drawn at levels equally spaced in the logarithm of $\mathrm{d}^2f/\mathrm{d}v_\mathrm{r}/\mathrm{d}v_\theta$ from 0.01 to 1 (thinnest to thickest line).

correlates with local density (even though there is considerable scatter in the density-radius relation). The right-hand panel of Fig. 6 shows that such a morphology-density relation exists within our model also. Importantly, the figure demonstrates that such a relation exists even beyond 1 Mpc from the cluster centre, where no morphology-radius relation can be discerned.

Our current calculations include three environmental effects which may be driving these relations. These are: 1) galaxy merging, 2) tidal mass loss from galaxies and 3) starvation of galaxies (i.e. galaxies are unable to accrete fresh gas once they fall into a group or cluster and so their star formation rate rapidly declines). Using GALFORM it will be possible to ascertain which of these processes are contributing to building the morphology-density relation. Further processes which may be important (such as ram pressure stripping and tidally triggered star formation) will also be implemented and their importance determined.

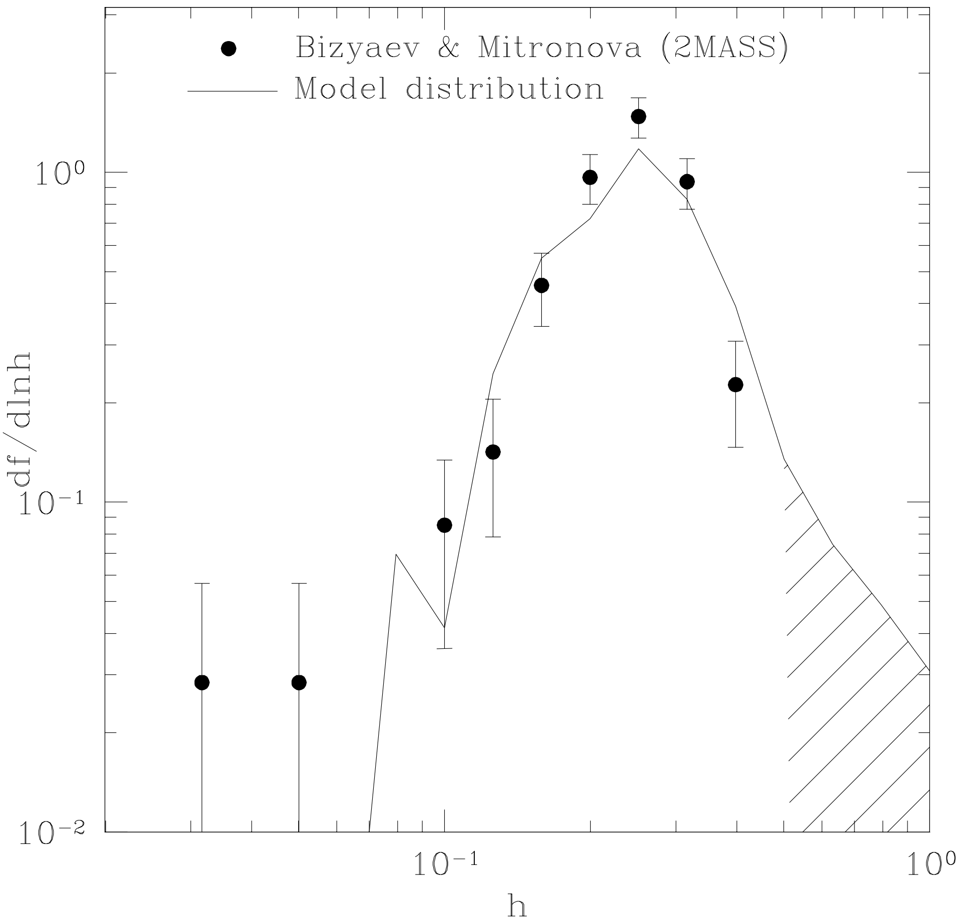

Figure 4. The normalized distribution of galactic disk scale-heights, h, in the observational sample of Bizyaev & Mitronova (2002) compared to the prediction of our model. Error bars on the observational data points indicate Poisson errors. The model prediction is shown by the solid line. The model galaxies have been weighted to match the distribution of absolute magnitudes and morphological types found in the observational sample.

4. Conclusions

Semi-analytic models such as GALFORM continue to be a highly fruitful means of studying the physical mechanisms involved in the process of galaxy formation. Continued development of the GALFORM model has allowed it to be applied to many novel problems (such as the thickening of galaxy disks) and is beginning to permit much more detailed studies of environmental effects than has previously been possible. A preliminary study of simulated clusters similar to Cl0024 shows that a morphology-density relation extending into the field arises naturally from the model. Future work will be directed at understanding the physics which is driving this relation.

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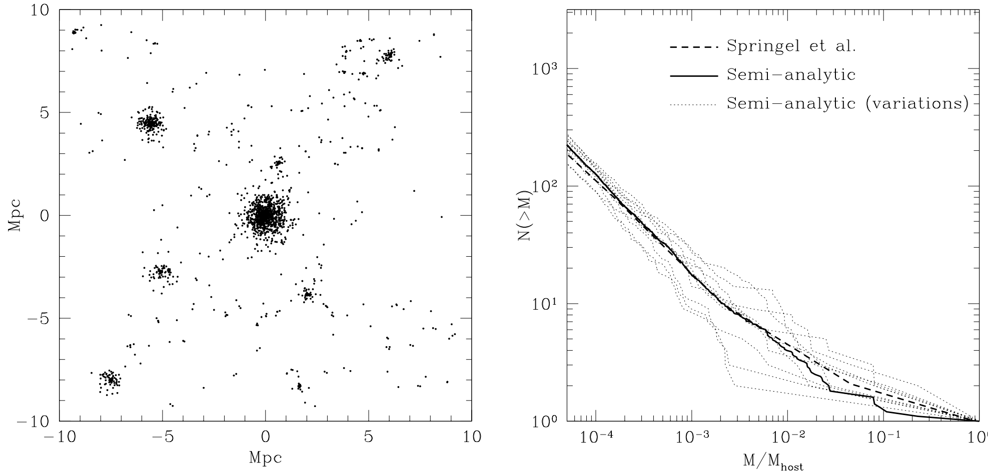

Figure 5. *Left-hand panel:* The projected distribution of model galaxies brighter than $m_{\mathrm{F814}} = 21.5$ in a 20 Mpc cube centred on a $z = 0.4$ cluster with mass similar to that of Cl0024 (approximately $8 \times 10^{14}h^{-1}M_{\odot}$). Each dot corresponds to an individual galaxy. Note the presence of several large groups of galaxies near the central cluster. *Right-hand panel:* The cumulative number of sub-halos in the central cluster as a function of their mass (expressed relative to the total cluster mass). The dashed line shows the result computed by Springel et al. (2001) from their N-body simulation, while the solid line shows the average mass function computed from the GALFORM model. Dotted lines show results from ten individual cluster realizations from GALFORM to illustrate the expected cluster-to-cluster variation in this quantity.

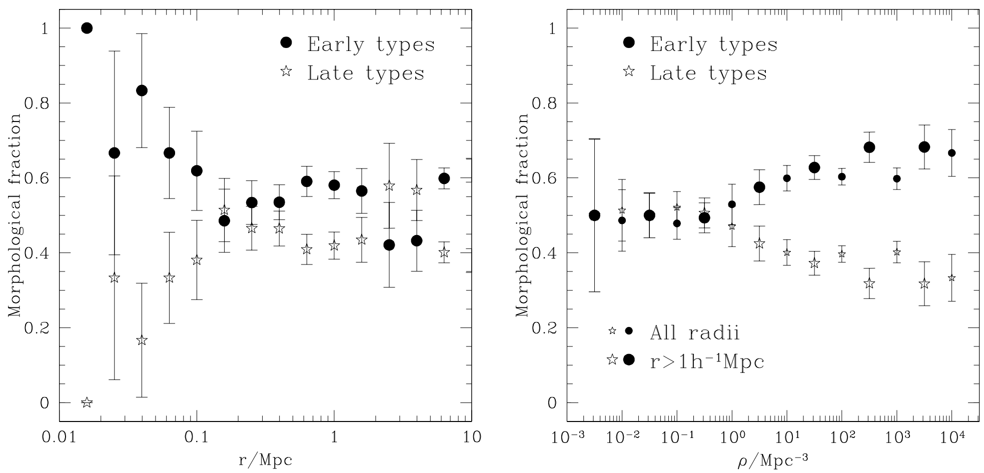

Figure 6. *Left-hand panel:* The morphology-radius relation in a model "Cl0024-like" cluster (and surroundings). Filled circles show the fraction of early-type galaxies as a function of radius, while stars show the corresponding fraction of late-type galaxies. Errorbars are calculated assuming a binomial distribution of early and late-types in each bin. At small radii the fraction of early-types increases as radius decreases. Beyond approximately 0.3 Mpc the morphological mix is constant. *Right-hand panel:* The morphology-density relation in the same model cluster (and its surroundings). Here circles and stars show the early and late-type fractions as a function of local, 3D galaxy number density (estimated from the distance to the tenth nearest neighbour for each galaxy in the sample). Small symbols show the relation including galaxies at all radii in the sample, while large symbols include only galaxies beyond 1 Mpc from the cluster centre.

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