The Dynamical Evolution of Galaxies in Clusters

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Abstract. The evolution of galaxies is driven strongly by dynamical processes including internal instabilities, tidal interactions and mergers. The cluster environment is a useful laboratory for studying these effects. I present recent results on simulations of interacting populations of spiral and elliptical galaxies in the cosmological collapse of a cluster, showing the formation of the central, brightest cluster galaxies through merging, the effect of tidal interactions and merging on galaxy morphology over cosmic history, and the distribution and kinematics of the tidal debris field. (See www.cita.utoronto.ca/∼dubinski/rutgers98 for figures and animations.)

1. Introduction

In most cosmological scenarios, galaxies form early and rapidly in the collapse of density perturbations but continue to evolve over a Hubble time both in luminosity and morphology. The ageing of the galaxy stellar population leads to a gradual dimming of their light, a signal that is now picked up in distant spirals and elliptical galaxies (e.g. Vogt et al. 1996; Kelson et al. 1997) Dynamics primarily drives the galaxy morphological evolution through: 1) internal gravitational instabilities such as the bar instability which may influence bulge formation, 2) tidal interactions which can explain much of the "disturbed" and irregular morphology of galaxies at high z (e.g. Oemler et al. 1997) 3) the merging of disks to form some or most of the ellipticals (Toomre 1977). Merging obviously contributes to evolution of the galaxy luminosity function.

Galaxy clusters are the best place to investigate the connection between dynamics and morphology because they contain a diverse population of galaxies that have interacted strongly many times over their lifetime. Dressler (1984) has aptly described clusters as laboratories of galaxy formation, in particular in the way they emphasize the importance of gravitational interactions. Here, I explicitly follow that lead by setting up numerical experiments of galaxy interactions in cosmological clusters.

The simulation of galaxy dynamics in a cosmological context at sufficient resolution to resolve detailed dynamical effects is now becoming feasible. Kiloparsec scales can now be resolved in the volume surrounding a collapsing cluster. Most aspects of the dynamical evolution of galaxies do not require the complicated details of dissipative galaxy formation, so there is no need for expensive hydro calculations.

A simple technique that allows studies of galaxy dynamics in clusters works as follows. First, a cosmological N-body simulation in a large volume is run and a cluster size dark halo is identified at $z = 0$. The simulation is re-examined at early times ($z = 3$ to 2) and all dark halos that will end up in the cluster are replaced with N-body models of disk (and possibly elliptical) galaxies scaled according the mass and circular velocity of the halos with at least $10\times$ the resolution. The rationale is that galactic disks should form rapidly prior to cluster collapse and the bulk of their dynamical evolution will be driven by the interactions they experience when they fall into the collapsing cluster. Simulations are then continued with the resolved galaxy models to $z = 0$.

So far I have applied this technique in 2 simulations: the first with a poor cluster ($\sigma = 550$ km/s) containing 100 well-resolved disk galaxies inserted at $z = 2$ (Dubinski 1998) and a Virgo-scale cluster ($\sigma = 800$ km/s) with 200 disks and 15 ellipticals inserted at $z = 3$. The main results of these simulations are discussed below.

2. Brightest Cluster Galaxies

Most clusters have a giant elliptical or cD galaxy near their spatial and kinematic center. (They are generically known as brightest cluster galaxies or BCGs). There have been various theories put forward for the origin of these galaxy giants including star formation in X-ray cooling flows (Fabian 1994), galactic cannibalism and tidal destruction of small galaxies (Richstone 1976; Ostriker & Tremaine 1975), and early galaxy merging during the collapse of cluster core in hierarchical structure formation (Merritt 1985). There is little evidence of young stars in BCG's which refutes the cooling flow idea and galactic cannibalism can only account for a small fraction of the luminosity of a BCG since merging is inefficient in virialized clusters – galaxies are moving fast and tidally truncated so dynamical friction timescales are too long to allow much merging.

The idea that seems to work the best is rapid galaxy merging in a cosmological hierarchy and has recently been illustrated by Dubinski (1998) in a simulation of a poor cluster. The 7 most massive galaxies in the collapsing cluster merge rapidly forming a BCG by $z \sim 1.0$ building up the bulk of its luminosity. The BCG accretes a further 6 "dwarf" galaxies ($v_c \sim 100$ km/s) but they do not add much extra mass. The structure and kinematics of the resulting simulated BCG agree quantitatively with real ones (cf. Fisher et al. 1995) with de Vaucouleurs light profiles ($r_e \approx 20$ kpc) and central velocity dispersions in the right range $\sigma \approx 350$ km/s). Furthermore, the BCG displays the alignment effect: its long axis is closely aligned with the long axis of the galaxy distribution (Sastry 1968; Carter & Metcalfe 1980). This can be traced back to the collapse of the cluster along the filament present in the cosmological initial conditions supporting conjectures that BCG's show alignment correlations with large-scale structure (Binggeli 1982).

3. Strong Tidal Interactions and Merging

Moore et al. (1996) have pointed out that strong tidal interactions or galaxy "harassment" in the cluster environment play an important role in galaxy morphological evolution. In the simulations discussed here, *most* galaxies show signs of tidal disturbance over their history. Some major effects are the excitation of open spiral structures, warps and even tidal tails in close encounters of individual galaxies with the growing central BCG. Many galaxies are on orbits that take them within 100 kpc of the cluster center and the tidal fields within this radius are sufficient to obviously distort galaxies. Isolated disturbed galaxies seen in clusters may result in high speed encounters with the parent cluster's central potential. Higher resolution simulations of individual disks in orbit in fixed cluster potentials clearly demonstrate this effect (Dubinski & Hayes 1999). Tidal heating of disks can be strong in this environment and could account in part for the greater frequency of S0 galaxies in clusters as revealed by the morphology-density effect (Dressler 1980).

Galaxy-galaxy interactions also create disturbed galaxies but this occurs mainly in bound pairs or groups which eventually merge forming elliptical-like remnants. It appears that the general origin of elliptical galaxies in the cluster environment is the merging of sub-groups in the hierarchy. Moore et al. (1998) claim that galaxy harassment may also produce dwarf elliptical galaxies but to be definitive higher resolution is needed since numerical heating effects can be severe when simulating galaxies over a Hubble time even when using 100K particles. All of this work needs to be placed on a stronger, statistical foundation with more simulations and better resolution.

4. Intergalactic Tidal Debris

Cluster tides are quite effective at stripping stars from galaxies and building up an intergalactic stellar population and potentially account for the envelopes of the cD galaxies (Richstone 1976; Merritt 1985). The recent discovery of intergalactic stars in the Virgo and Fornax clusters in the form of planetary nebulae and red giant-branch stars (Theuns & Warren 1996; Arnaboldi et al. 1996; Feldmeier et al. 1998; Ferguson et al. 1998) along with the likelihood of intergalactic globular clusters have revived interest in the dynamics of the tidal-stripping process.

Analysis of the poor cluster simulation shows that about 10% of the stars are distributed diffusely throughout the cluster with surface brightness dimmer than $\mu = 26.5$ assuming an $M/L = 5$ (Dubinski, Murali, & Ouyed 1999). The radial light distribution is approximately a continuation of a deVaucouleurs profile out to $r = 1$ Mpc from the center of the BCG. The Virgo-cluster simulation shows similar results and there is the hint of a cD envelope.

There are also a significant number of streams and swathes of stars in the intracluster light that originate in stripping events of spirals and ellipticals. These streams often trace the orbits of galaxies on radial orbits that have suffered a strong, tidal encounter with the cluster center. Examples of streams just forming in tidal encounters have recently been detected in the Coma cluster (Gregg and West 1998). Streams may be difficult to detect directly because of their low surface brightness. However, the contrast may increase when viewed in the $r - v_{los}$ phase-plane. A kinematic survey of several hundred planetary nebulae and globular clusters in the intergalactic space surrounding M87 in Virgo or NGC 1399 in Fornax may reveal coherent streams on top of a diffuse population. New analysis shows how the kinematics of the tidal debris streams present a new way to measure the gravitational potential of nearby clusters (Dubinski et al. 1999).

5. Conclusions

The simulations described here provide a detailed, quantitative way of probing the dynamical evolution of galaxies in clusters. Future work will concentrate on producing a simulated survey of clusters covering a wide mass range in different cosmological models to improve statistics on the BCGs and the elliptical population along with general effects of tidal interactions on galaxy morphology over cosmic history. In principle, these effects depend strongly on the cosmological model so detailed comparison with the observations will provide interesting constraints and consistency checks on these models.

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References

Arnaboldi, M. et al. 1996, ApJ, 472, 145
Binggeli, B. 1982, A&A, 107, 338
Carter, D. & Metcalfe 1980, MNRAS, 191, 325
Dressler, A. 1980, ARAA, 22, 185
Dressler, A. 1984, ARAA, 22, 185
Dubinski, J. 1998, ApJ, 502, 141
Dubinski, J. & Murali, C. & Ouyed, R. 1998, submitted
Dubinski, J. & Hayes, W. 1999, in preparation
Fabian, A. 1994, ARAA, 32, 277
Feldmeier, J., Ciardullo, R., & Jacoby, G. 1998, ApJ, 503, 109
Ferguson, H. C., Tanvir, N. R., & Von Hippel, T. 1998, Nature, 391, 461
Fisher, D., Illingworth, G., & Franx, M. 1995, ApJ, 438, 539
Gregg, M. D., & West, M. J. 1998, Nature, in press
Kelson, D. D. et al. 1997, ApJ, 478, L13
Merritt, D. 1985, ApJ, 289, 18
Moore, B. et al. 1996, Nature, 379, 613
Moore, B., Katz, N. & Lake, G. 1998, ApJ, 495, 139
Oemler Jr., A., Dressler, A., Butcher, H.R. 1997, ApJ, 474, 561
Ostriker, J. & Tremaine, M. 1975, ApJ, 202, L113
Richstone, D. O. 1976, ApJ, 204, 642
Sastry, G.N. 1968, PASP, 80, 252
Theuns, T., & Warren, S. J. 1996, MNRAS, 284, L11–L15
Toomre, A. 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B.M. Tinsley and R.B. Larson (New Haven: Yale Univ. Obs.), p. 401.
Vogt, N. et al. 1996, ApJ, 465, 15