GALAXY HARASSMENT—INTERACTIONS FOR THE 90s

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1. Introduction

The origin of the Hubble sequence remains a long-standing puzzle in astronomy. Giant galaxies range from slowly-rotating dense ellipticals to thin late-type spiral disks. At the faint end, there are two distinct classes of "ellipticals/spheroids" that are easily separated in plots of nearly any two of their properties, such as central surface brightness versus luminosity (Ferguson and Binggeli 1994; Kormendy 1985). The elliptical class includes the bright giants and extends to the rare high surface brightness "dwarf ellipticals", M32 being the prototype. The "spheroidal" galaxies have low surface brightnesses and are all $\gtrsim 3$ magnitudes fainter than L_*, the characteristic break in the luminosity function. The dwarf spheroidal galaxies (dSph) in our Local Group of galaxies with magnitudes in the range $-8 \gtrsim M_{\rm B} \gtrsim -12$ are often considered to be the low luminosity extreme of this sequence, but nearly all other known galaxies in this class reside in clusters.

There is no shortage of theories for galaxy formation and the origin of the Hubble sequence. Several speakers at this conference have described formation via merging (Toomre 1977) and "chaotic collapse" (Lake and Carlberg 1988). Spheroidal formation theories have a shorter history and have focused on incremental changes to the giant galaxy theory. There are many problems with the scheme that combines the notion of lower amplitude peaks in the hierarchical model with the use of stellar winds or supernovae to expel gas from small galaxies (Dekel and Silk 1986, Vader 1986). The clustering properties of dwarfs is opposite to the expectations

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of the Dekel and Silk model (Ferguson and Binggeli 1994). The model also has the seemingly impossible chore of explaining the general properties of both rapidly-rotating gas-rich dwarfs and gas free dwarf spheroidals.

Hubble Space Telescope (*HST*) observations reveal that the morphologies of galaxies in clusters changed dramatically since $z \sim 0.4$. Over 20 years ago, Butcher and Oemler (1978, 1984) discovered a large population of "blue galaxies" in clusters at $z \sim 0.4$. Giant ellipticals are already in place at $z \sim 0.4$, but the ubiquitous "blue galaxies" are distorted spirals that have vanished from present-day clusters (Dressler et al. 1994a). The population difference is greatest for galaxies fainter than $L_*/5$: 90% are bulgeless "Sd" disk systems in distant clusters, whereas 90% are spheroidals in nearby clusters (Sandage et al. 1985). Couch et al. (1994) present spectroscopic evidence that the distorted blue galaxies at $z \sim 0.3$ have undergone multiple burst events separated by 1–2 Gyr. In hierarchical clustering models, the influx of field galaxies into clusters peaks at $z \sim 0.4$ (Kauffmann 1995). So, we need to transform these galaxies when they enter clusters.

At speeds of several thousand kilometers per second, close encounters with bright galaxies cause impulsive gravitational shocks that can severely damage the fragile disks of Sc–Sd galaxies. Our earlier analytical work revealed that these collisions are frequent enough that disk galaxies would be harassed throughout a cluster (Moore et al. 1996a). Moore et al. (1996b) used numerical simulations to compare harassed galaxies to *HST* frames of galaxies in clusters at $z \gtrsim 0.3$. They stated that the cumulative effect of such encounters changes a disk galaxy into a spheroidal galaxy, thus identifying the present-day remnants of the disturbed blue galaxies and explaining the change in galaxy morphologies in clusters since $z \sim 0.4$. Moore et al. (1998) provide detailed comparisons of the harassed remnants with the photometric and kinematical properties of dwarf spheroidal galaxies. Lake et al. (1998) consider the feeding of quasars by galaxy harassment. We will review this work adding a few recent results.

2. Modeling Galaxy Harassment

We take a "minimalist" approach in our simulations. It is difficult to imagine how any galaxy could avoid the effects that we simulate. Our cluster models are based on properties of the Coma cluster with galaxies drawn from a Schechter luminosity function, assigned dispersions based on the Faber-Jackson relation and then tidally limited based on the pericenter of their cluster orbits. Galaxy harassment is slightly more effective at removing mass than tides alone. Our "victims" lose as much as half of their mass over a period of 3–5 Gyr. We reduced the initial galaxy masses by the time average of 25%. We expected that this was overly conservative as the largest galaxies do the harassing and are rather immune to it themselves.

Recently, we simulated the evolution of the dark matter in clusters of galaxies. The final state of the simulation has over a thousand identifiable "galactic halos" with masses that demonstrate that our assumptions about the masses of galactic halos within clusters were indeed conservative (Moore et al. 1998). We were also conservative in our choice of orbits for the harassment victims. At a fixed mean orbital radius, galaxies on elongated orbits experience greater harassment. We follow galaxies that have apo/peri ratios of 2 (*e.g.* apocenter at 600 kpc, pericenter at 300 kpc), whereas the typical value in a cluster with isotropic dispersions is ~ 6. As a result, our model galaxies avoid extremes of the cluster distribution and start with large dark halo masses determined by the tidal limit at their atypically large pericenters. The full details of the simulations can be found in Moore, Lake and Katz (1998).

If we assume that spiral disks follow the Tully-Fisher relationship ($L \propto v_{\rm circ}^4$) and are experiencing impulsive fly-by collisions from other galaxies that are tidally limited within a larger virialized system, we find a remarkable result. *The timescale to shake a disk into a spheroidal system is independent of the mass of the larger virialized system and independent of the orbital radius of the spiral disk within that virialized system.* Realistic conditions limit the validity of such universal statements. Galaxies with larger circular velocities are earlier type systems. High density bulges are effective at protecting disks from damage owing to encounters. Low surface brightness galaxies are more easily harassed. Even if they follow the Tully-Fisher relationship, the slower inner rise of their rotation curves increases the response to impulsive shocks. The impact parameters become too large at the edges of rich clusters for the collisions to be impulsive. Similarly, the velocities can be too slow in smaller groups, leading to merging rather than harassment. However, galaxy harassment is not just for rich clusters. It will occur anytime that galaxies are moving past one another at speeds that are much larger than their circular velocities. The three-dimensional dispersion velocity of a group with a total luminosity of just 10 L_* is ~ 700 km s^{-1}. Harassment will certainly occur in such an environment.

3. The Harassment Drama

The evolution proceeds in a violent, chaotic fashion that is best appreciated by watching the published video (Moore, Lake and Katz 1998). Typically, the first encounters create "disturbed barred spirals" with sharp and dramatic features drawn out from the dynamically cold disk. Tails of material can be pulled out and distorted by the tidal field of the cluster (Figure 1). The gas distribution often forms ring structures that tumble within the

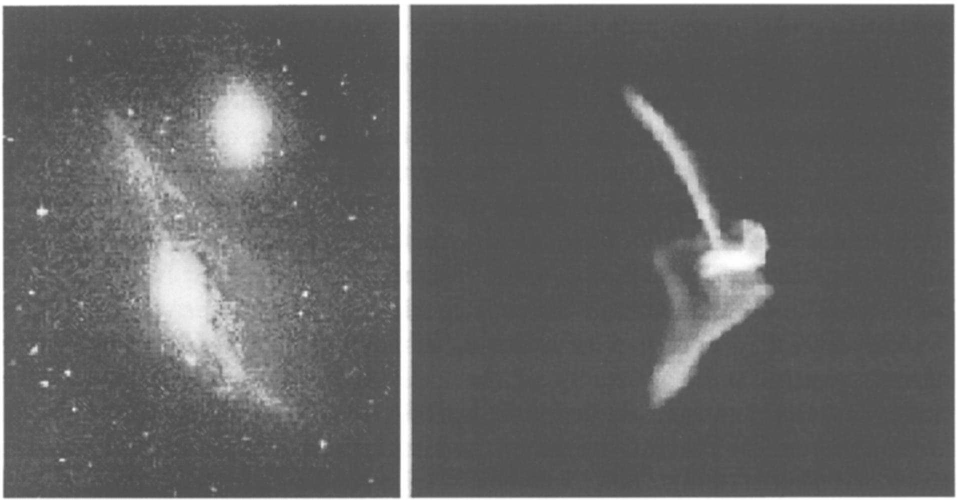

Figure 1. NGC 4438 is a Virgo cluster galaxy (left) with strong tidal tails. In our simulations, one of the first strong collisions often makes features such as those seen on the right. Combes (et al. 1988) constructed a model where the distortions owe to the optical companion. In their model, the true separation of the two galaxies is 100 kpc. There are many other galaxies that are closer and more massive, making them better candidates for the disturbance. Harassment is not too gentle to explain NGC 4438, as asserted by J. Kenney at this conference.

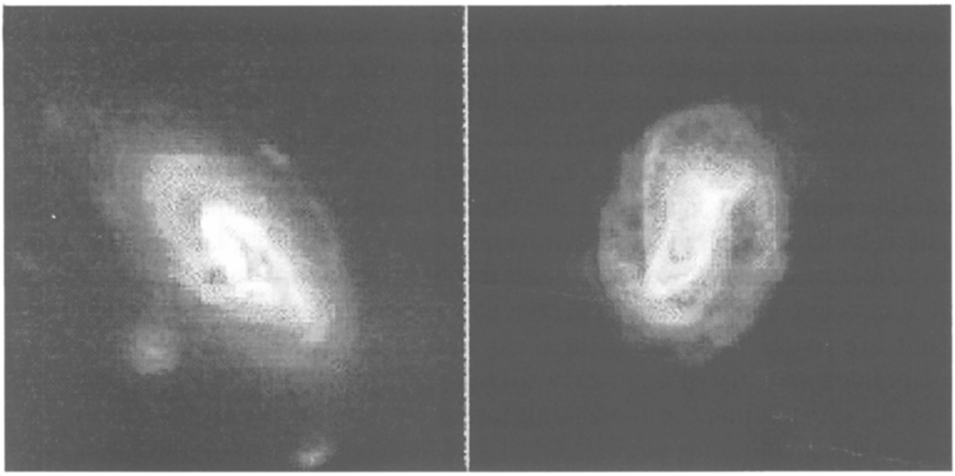

Figure 2. The left image is a spiral galaxy with a prominent ring in the distant rich cluster CL0939. The ring structure on the right is common in our simulations.

stellar bar (Figure 2).

The evolution is driven by just a few close encounters. These drive the multiple starbursts inferred from *HST* data (Barger et al. 1996). Another observational puzzle has been the ubiquity of disturbed galaxies with no

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sign of current interaction (Dressler et al. 1994b). Over the course of 3 Gyr, the closest approach of another galaxy is normally greater than 30 kpc. Since the relative velocity of strong encounters is ~ 1500 km s^{-1}, and the velocity impulse internal to the galaxy is $\lesssim 50$ km s^{-1}, the perturbing galaxy moves $\sim$ 100 kpc by the time the disk's response is noticeable. The galaxy delivering the shock is an L_* or brighter elliptical and barely noticed that it happened, eliminating the concern that one must simulate the internal response of the harasser (Joseph 1996).

4. The Spheroidal Remnants

After several strong encounters, angular momentum loss combined with impulsive heating, leads to a prolate figure supported equally by random motions and rotation. The gas sinks to the very center of the galaxy and the stellar distribution is heated to the extent that it closely resembles a dwarf elliptical, although some remnants retain very thick stellar disks and would be classed as dwarf lenticulars. At this stage in the evolution, encounters cease to create sharp distortions and fail to remove any more material from the compact remnant.

Moore, Lake and Katz (1998) make extensive comparisons of the harassed remnants to spheroidal galaxies in nearby clusters (Ferguson and Binggeli 1994; Kormendy 1985). We found good agreement with the luminosity function, surface brightness profiles, flattening, internal kinematics, mass-to-light ratios, stellar populations and clustering properties. This can't be much of a surprise. Disks exist in clusters at $z \sim 0.3$ and are mostly gone in present-day clusters, replaced at the faint end of the luminosity function by spheroids. We've shown that gravitational interactions with large galaxies drives such a transformation. The fact that the properties match suggests that other physical processes like ram pressure are unlikely to be important.

One might hope that radial gradients of the spheroidal populations would provide interesting tests of the model. However, the most important effect is independent of how the spheroidals formed: global tides coerce the lowest density (or surface brightness) objects into the diffuse stellar background (Ciardullo et al. 1997). Most radial correlations are projections of the fundamental correlation between density and survivability:

- only the densest spheroidals survive in the inner parts of the clusters, creating a paucity of faint spheroids there (Bernstein et al. 1995)
- correlations between density and color/metallicity create color gradients in the surviving ensemble (Secker 1996)
- the fraction of the more robust nucleated spheroidals increases towards the center (Binggeli et al. 1987)

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- selective destruction of non-nucleated spheroidals with small pericentric radii can lead to a central deficiency in radial orbits causing a dip in the cluster's line-of-site velocity dispersion
- spiral disks seen in the central regions of clusters owe to projection, their velocity fields won't show virialization (Tonry, Ajhar and Luppino 1990; Bernstein et al. 1994)
- in the outer parts of the clusters, spirals on radial orbits are transformed faster than those on nearly circular orbits (Dressler 1986)

5. Feeding Quasars

When we first simulated a harassed galaxy with gas, we were aghast to see up to 90% of the gas was driven into the inner 500 pc in a few Gyr. Up to half of that mass can be transferred in a burst lasting just 100-200 Myr. This transport of gas to the center of a galaxy is far more efficient than any mechanism proposed before.

There are two observations that suggest that harassment could be important for feeding quasars at intermediate redshifts $0.2 \lesssim z \lesssim 0.8$ (Lake, Moore and Katz 1998). Quasars at intermediate redshifts are in Abell richness class 0-1 clusters of galaxies—an environment that is considerably richer than that of lower redshift quasars (Yates, Miller and Peacock [1989] find the break occurs at $z \sim 0.3$, while Yee and Ellingson [1993] state that it occurs at $z \sim 0.6$). There is evidence that many quasar hosts are less luminous than L_* at $z \sim 0.3$ (Bahcall, Kirhakos and Schneider 1995).

After observations of additional quasars, Bahcall et al. (1997) conclude that, "the luminous quasars studied in this paper occur preferentially in luminous galaxies". They reject the "null hypothesis" that all galaxies are equally likely to have quasars (e.g. a hypothesis that states that Draco and M87 are equally likely to host quasars). Their conclusion results because at least half of all galaxies are $\gtrsim 2$ magnitudes fainter than L_* whereas the dividing line for their sample of quasar hosts is $\sim L_*$ within their errors. Popular luminosity functions diverge at the faint end ($N \propto L^{-x}$, $1.5 > x > 1$), requiring a cutoff to define an "average luminosity" that is always 2-3 magnitudes brighter than the cutoff or $\gtrsim 2$ magnitudes fainter than L_*.

However, galaxies brighter than $\sim 0.75 L_*$ contain half of all the luminosity. This dividing line of luminosity is consistent with the Bahcall et al. midpoint of quasar hosts within their errors. The simplest summary of the observations to date is that quasars and galaxies may be related in the same way as stars and galaxies: the probability of finding either in a galaxy is proportional to the galaxy's luminosity but their individual luminosities are not determined by the luminosity of their host. *We need a mechanism at $z \sim 0.3$ that triggers quasars with a frequency that is roughly* *proportional to galaxy luminosity and prefers clusters. A mechanism that only operates in bright galaxies in the field such as mergers can not be the dominant trigger at* $z \sim 0.3$.

If galaxy harassment triggers quasars, we make four clear predictions:

1. QSO hosts will be found in systems where harassment occurs;
2. AGN frequencies are enhanced in clusters undergoing harassment;
3. resolved hosts should appear disturbed;
4. black holes should exist in some nucleated spheroidal galaxies.

Detailed discussions of these points can be found in Lake et al. (1998). Most if not all of the quasars with sub-L_* hosts are in high density environments. The *HST* images of the host candidates show tantalizing evidence of distortions (Bahcall, Kirhakos and Schneider 1995). There is an ongoing controversy with respect to the frequency of AGNs in Butcher-Oemler clusters, but we note that quasars at intermediate redshifts could not lie in clusters rich enough to be classified by Abell if nuclear activity were not enhanced in clusters. The final prediction suggests black hole hunting should be undertaken in some new places. In our original paper, we pointed to NGC 4486B as an interesting place to look, though one might argue whether it is an appropriate galaxy to consider in the context of harassment. Since then, Kormendy et al. (1997) have detected a substantial black hole in this galaxy.

To summarize, disk galaxies are seen in clusters at $z \sim 0.3$. We simulate the gravitational shocks that these galaxies feel when other galaxies in the clusters pass by them. The only thing that we need to know about the other galaxies are their masses. We adopted conservative values for these masses and the orbital distributions of the "victims". *We see absolutely no way that galaxies in clusters can avoid the gravitational interactions that we call harassment.* These interactions produce the distorted galaxies seen with *HST*. The collision frequency matches the interval between starburst events (Barger et al. 1995). The galaxies are transformed into spheroidal systems like those observed in clusters today. Quasar feeding depends on the flow of gas into the center; this could easily be stopped by star formation. As for the rest of our harassment results, the greatest uncertainty that remains in the model is the strength of tides in the very center of clusters of galaxies (*cf.* Moore et al. 1998). For this reason, we avoid simulating galaxies with orbits that have pericenters less than 150 kpc.

Galaxies are metamorphosed by their mutual interactions. "Merging" of spirals in groups creates bright ellipticals. In a cluster, one of these "cannablizes" its neighbors to become the giant central elliptical. The spheroidal galaxies are created by the harassment of low luminosity spirals. Our work to date has only touched on some of the most dramatic changes, the aetiology of harassment promises to be even richer than that of merging and cannibalism.

References

Bahcall, J. N., Kirhakos, S., Saxe, D. H. and Schneider, D. P. 1995, *Ap. J.*, **479**, 642.

Bahcall, J. N., Kirhakos, S. and Schneider, D. P. 1995, *Ap. J.*, **450**, 486.

Barger, A. J., Aragon-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I. and Sharples, R. M. 1996, *M.N.R.A.S.*, **279**, 1.

Bernstein, G. M., Nichol R. C., Tyson J. A., Ulmer M. P. & Wittman D. 1995, *A.J.*, **110**, 1507.

Binggeli B., Tammann, G. A. and Sandage, A. 1987, *A.J.*, **94**, 251.

Butcher H. and Oemler A. 1978, *Ap.J.*, **219**, 18.

Butcher H. and Oemler A. 1984, *Ap.J.*, **285**, 426.

Ciardullo, R., Jacoby, G., Feldmeier, J. and Bartlett, R. 1997, *Ap.J.*, in press.

Combes F., Dupraz C., Casoli F. and Pagani L. 1988, *Astr.Ap.*, **203**, L9.

Couch, W. J., Ellis R. S., Sharples R. and Smail I. 1994, *Ap.J.*, **430**, 121.

Dekel, A. and Silk, J. 1986, *Ap.J.*, **303**, 39.

Dressler, A. 1986, *Ap. J.*, **301**, 35.

Dressler, A., Oemler A., Butcher H. and Gunn J.E. 1994a, *Ap.J.*, **430**, 107.

Dressler, A., Oemler A., Sparks W.B. and Lucas R.A. 1994b, *Ap.J.Lett.*, **435**, L23.

Ferguson, H.C. and Binggeli B. 1994, *Astr. Ap. Rev.*, **6**, 67.

Joseph, B. 1996, *Nature*, **379**, 586.

Kauffmann, G. 1995, *M.N.R.A.S.*, **274**, 153.

Kormendy, J. 1985, *Ap.J.*, **295**, 73.

Kormendy, J., Bender, R., Magorrian, J., Tremaine, S., Gebhardt, K., Richstone, D., Dressler A., Faber, S. M., Grillmair, C. and Lauer-T-R. 1997, *Ap.J.Lett.*, **482** L139.

Lake, G. and Carlberg, R. G. 1986a, *A.J.*, **96**, 1581.

Lake, G., Moore, B. and Katz, N. 1998, *Ap. J.*, in press.

Moore, B., Governato, F., Quinn, T., Stadel, J. and Lake, G. 1998, *Ap. J.*, submitted.

Moore, B., Katz, N. and Lake, G., 1996, *Ap. J.*, **457**, 455.

Moore, B., Lake, G. and Katz, N. 1998, *Ap. J.*, in press.

Moore, B., Katz, N., Lake, G., Dressler, A. and Oemler, A. 1996, *Nature*, **379**, 613.

Sandage, A., Binggeli, B. & Tammann, G.A. 1985, *A.J.*, **90**, 1759.

Secker, J. 1996, *Ap.J.Lett.*, **469**, L81.

Tonry, J. L., Ajhar, E. A. and Luppino, G. A. 1990, *A.J.*, **100**, 1416.

Toomre, A. 1977, In *The Evolution of Galaxies and Stellar Populations*, ed. B.M. Tinsley and R.B. Larson, p. 401, (New Haven: Yale University Observatory).

Vader, P. 1991, *Ap.J.*, **305**, 669.

Valluri, M. and Jog, C. J. 1991, *Ap.J.*, **374**, 103.

Yates, M. G., Miller, L. and Peacock, J. A., *M.N.R.A.S.*, 240, 129.

Yee, H. K. C. and Ellingson, E. 1993 *Ap. J.*, 411, 43.