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The Formation of Quasars in Low Luminosity Hosts via Galaxy Harassment

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ABSTRACT

We have simulated disk galaxies undergoing continual bombardment by other galaxies in a rich cluster. "Galaxy harassment" leads to dramatic evolution of smaller disk galaxies and provides an extremely effective mechanism to fuel a central quasar. Within a few billion years after a small disk galaxy enters the cluster environment, up to 90% of its gas can be driven into the inner 500 pc. Up to half of the mass can be transferred in a burst lasting just 100-200 Myr. This transport of gas to the center of galaxy is far more efficient than any mechanism proposed before. Galaxy harassment was first proposed to explain the disturbed blue galaxies in clusters seen in clusters at ($z \gtrsim 0.3$), the "Butcher–Oemler effect". Quasars at the same reshifts lie in more clustered environments than those at lower redshift. Recent HST observations find that roughly half of all observed quasar host galaxiess are fainter than L_*, with many of these less luminous hosts occuring at redshifts $z \gtrsim 0.3$. We examine 5 quasars that are claimed to have low luminosity hosts and find that 3 are in rich clusters of galaxies, the fourth may be in a cluster but the evidence for this is marginal. The environment of the fifth has not been studied.

Subject headings: galaxies: clusters, galaxies: active, (galaxies:) quasars: general, galaxies: evolution

1. Introduction

To power the central black hole by accretion, bright quasars must consume $10^8 - 10^9$ solar masses during their lifetimes—roughly 1% of the stellar mass in a bright elliptical galaxy or 10% of the gaseous mass of a bright spiral. Even with the assumption of a large host galaxy, an efficient mechanism is needed to channel gas to the central source. This problem of fuelling quasars is normally divided into three parts: the movement of gas from galactic scales to the inner few hundred parsecs, the instabilities of a self gravitating disk that transports the gas to a compact accretion disk and the detailed dynamics and radiation mechanisms of the final accretion. Here, we consider the first problem of moving gas from galactic scales into the inner few hundred parsecs. At redshifts of 2 where the number densities of quasars peak, this has been associated with the dynamical chaos of galaxy formation (c.f. Haehelt and Rees 1993). At lower redshifts, interactions of galaxies leading to coalescence or merging have been proposed (Hernquist 1989). These mergers can drive more than 10% of the gas to the center. The final host galaxy is the product of a merger, therefore it would be brighter than average.

There are two observations that suggest a third mechanism at intermediate redshifts $0.2 \lesssim z \lesssim 0.8$. The environment of quasars has been observed to change with redshift (Yates, Miller and Peacock 1989; hereafter YMP89, Yee and Ellingson 1993; hereafter YE93). Quasars at higher redshifts are in Abell richness class 0-1 clusters of galaxies—an environment that is considerably richer than that of lower redshift quasars (the break point is at $z \sim 0.3$ in YMP89 and $z \sim 0.6$ in YE93). Bahcall, Kirhakos and Schneider (1995; hereafter BKS) used HST to image eight luminous quasars at redshifts between 0.15 and 0.3. Only three quasars in their sample have candidate hosts that are as luminous as L_*, the characteristic luminosity in the Schechter (1976) luminosity function (LF). The other five hosts must be fainter than L_* to have escaped detection.

After observations of additional quasars, Bahcall et al. (1997; hereafter BKSS97) conclude that "the luminous quasars studied in this paper occur preferentially in luminous galaxies". They are rejecting the "null hypothesis" that all galaxies are equally likely to have quasars (e.g. a hypothesis that states that Draco and the Milky Way 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. This depends slightly on the logarithmic slope of the LF. Since most LFs are weakly diverging at the faint end $N \propto L^{-x}$, $1.5 > x > 1$, a faint end cutoff is required to to define an "average luminosity" and that average is normally 2 to 3 magnitudes brighter than the cutoff or $\gtrsim$ 2 magnitudes fainter than L_*.

However, galaxies brighter than $0.7 - 0.8 L_*$ contain half of all the luminosity, where the range takes into accounts the uncertainty in the faint end slope and cutoff of the luminosity function. This dividing line of luminosity is consistent with the BKSS97 midpoint of quasar hosts within their errors. So, quasars don't obviously prefer brighter galaxies any more than stars do. Previously, McLeaod and Rieke (1995) suggested a linear relation between the absolute magnitude of the quasar and its host. BKSS97 find no such relation other than what can be attributed to the obvious bias from detection limits. The simplest summary of the observations to date is that quasars and galaxies may be related much as stars and galaxies; the probability of finding either in a galaxy is proportional to the galaxies luminosity but their individual luminosities are not determined by the luminosity of their host. Hence, *we need a mechanism that will produce quasars with a frequency per unit luminosity rather than a mechanism that only operates in bright galaxies as would be the case if mergers were the dominant trigger.*

We have found a mechanism that is extremely efficient at channeling gas into the center of sub-L_* galaxies that live in clusters. "Galaxy harassment" drives dynamical instabilities that send most of the gas into the central few hundred parsecs of the harassed galaxies. In §2, we present detailed hydrodynamical simulations that show these effects, while we look at the model's predictions in §3.

2. Description of the Simulations

We use TREESPH (Hernquist and Katz 1989, Katz, Weinberg and Hernquist 1996) to examine the fate of a high resolution galaxy with 2^{14} particles in each of three components: gas, stars and dark matter. The simulations were originally performed to follow the morphological evolution of galaxies in clusters (Moore *et al.* 1996, Moore, Katz and Lake 1996b), so the parameters were chosen to be typical of the disturbed galaxies seen by HST at redshifts of ~ 0.3. We present three simulations, two with circular velocities of 160km s^{-1} and one with a circular velocity of 110km s^{-1}. Using the Fisher–Tully (1981) relation, the luminosity of a galaxy with a circular velocity, $v_{circ} = 160$km s^{-1} is $\sim L_*/5$. The $L_*/5$ model galaxies have exponential disks with scalelengths of 2.5 kpc and scaleheights of 200 pc. The smaller galaxy is scaled by using the Faber-Jackson relation and preserving the ratio of stars, gas and dark matter. The disks are constructed with a Toomre (1964) "stability" parameter $Q = 1.5$ and run in isolation for 2 Gyr before being set into orbit in the cluster. The gaseous disk is initially on cold circular orbits.

The dark halo of each galaxy is a spherical isothermal with a core radius of $(v_{circ}/160\text{km s}^{-1})^2$ kpc, and is tidally truncated at the pericenter of the galaxy's orbit within the cluster. At 4 disk scalelengths (10 kpc), the initial ratio of dark matter to stars to gas is 11:4:1. At 8 disk scalelengths (20 kpc), the ratios are 20:5:1 and the total mass is $\sim 10^{11}(v_{circ}/160\text{km s}^{-1})^3\text{M}_\odot$.

The cluster model is based on Coma. Its one dimensional velocity dispersion is $\sigma_c = 1,000$km s^{-1} and the mass within the virial radius (1.5 Mpc) is $7 \times 10^{14} M_\odot$. For an M/L of 250, the total cluster luminosity within this radius is $2.8 \times 10^{12} L_\odot$. The other galaxies in the cluster are drawn from a Schechter (1976) luminosity function parameterized using $\alpha = -1.25$ and $M_* = -19.7$ including all galaxies brighter than $2.8 \times 10^8 L_\odot$ ($H_o = 100$km s^{-1}Mpc^{-1} and $\Omega = 1$ throughout this paper). This produces a model cluster that has 950 galaxies brighter than the Magellanic clouds, but only 31 brighter than L_*.

The masses and tidal radii of the other galaxies are determined by taking an isothermal model with a dispersion given by the Faber-Jackson relation and tidally limiting it at the galaxy's pericentric distance. They are then modeled by spheres with a softening length equal to half of their tidal radius. Most simulations have no "interpenetrating" collisions. However, any such collision will be more gentle than a collision with a realistic model of a galaxy that is more centrally concentrated. White and Rees (1978) speculated that the dark halos were stripped from galaxies within clusters; we find that the dominant stripping mechanisms are tides and high speed encounters—"galaxy harassment" (Moore, Katz and Lake 1996b; hereafter MKL96b). If galaxies are initially tidally limited by the cluster potential, bright galaxies retain more than half of their mass when followed for 5 Gyr. For greater self-consistency, we reduced the mass of each perturber by 25%, the average loss over a Hubble time (MKL96b) and we left the tidal/softening radius fixed. In the accompanying video, the perturbing galaxies are shown as green dots located at their centers.

The mean ratio of a perturbing galaxy's apocenter to its pericenter in our cluster model is roughly 6-to-1 (this ratio is even larger in infinite isothermal spheres with isotropic velocities); a galaxy found at a radius of 450 kpc will have a mean orbital radius of 400 kpc and a typical pericenter (r_{peri}) that is slightly greater than 150 kpc. We assign galaxies masses of $2.8 \times 10^{11}(r_{peri}/150\mathrm{kpc})(L/L_*)^{3/4}M_\odot$ corresponding to mass-to-light ratios, $M/L = 26h^2(r_{peri}/150\mathrm{kpc})(L/L_*)^{-1/4}$. The luminous parts of elliptical galaxies have mass-to-light ratios of $12hM_\odot/L_\odot$ (van der Marel 1991), so our perturbing galaxies have very modest extended dark halos.

The fraction of the cluster's density attached to galaxies varies with radius from zero at the center to nearly unity at the virial radius. It is ∼20% at the mean orbital radius of our simulated galaxies. The rest of the cluster mass is in a smoothly distributed background represented by a fixed analytic potential. Further details of the cluster model can be found in MKL96b.

We have intentionally made some conservative assumptions to ensure that our results are robust. For a model galaxy on a fixed orbit, the havoc wreaked by harassment depends on the square of the masses of the largest galaxies encountered. The most massive galaxies are giant ellipticals that are far less prone to harassment owing to their high internal densities, yet we have reduced the masses of all galaxies by the same time averaged value of 25%. At a fixed mean orbital radius, galaxies on elongated orbits experience greater harassment. We follow galaxies that have apo/peri ratios of 2 (*i.e.* apocenter at 600 kpc, pericenter at 300 kpc), whereas the typical value 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. Both effects serve to underestimate the effects of harassment.

The strongest encounters do not necessarily occur near the center of the cluster. Clearly, the frequency of encounters scales with the density of galaxies. However, there are two counterbalancing effects. If the galaxies are all tidally limited, they are more massive at larger cluster radii. Secondly, the relative velocity of encounters decreases in the outer parts of the cluster and encounters are stronger at fixed impact parameter. As long as the encounter timscale is short compared to the internal dynamical time of the galaxy, the gas dynamical effects are strongest outside the central region of a cluster. However, galaxies near the center of the cluster are more strongly damaged by the cluster's tidal field.

Care was taken to ensure that our initial models were sensible and stable by simulating galaxies on circular and elliptical orbits in smooth cluster potentials before examining the effects of harassment by other galaxies. The disk of a galaxy on circular orbit at 450 kpc in a fixed cluster potential remains stable for 10 Gyrs. A galaxy on an eccentric orbit with an apocenter of 600 kpc and pericenter of 300 kpc becomes bar unstable after the first pericentric passage and a bar persists for 5 billion years. Each passage through pericenter results in the loss of a small fraction of dark halo material, but the gas and stars remain attached.

The most dramatic evolution owes to strong encounters when the other perturbing galaxies are included (one simulation is shown on an accompanying video). The first strong encounter usually causes a bar instability of greater strength than that induced by only the cluster's tidal field. The continued heating of the disk by collisions transforms the galaxy into a spheroidal galaxy that matches the brightness profile and velocity dispersions of the dwarfs in nearby clusters (Moore, Lake and Katz 1997).

Perhaps the most stunning feature of the evolution is the rate that gas is driven into the center of the galaxy, as shown in Figures 1 and 2. Figure 1 shows snapshots of the evolution of gas disk (also shown as the last sequence in the accompanying video). The angular momentum of the gas is decreased by the torques of passing collisions and internal torques between the distorted disk and the halo. When combined with radiative cooling, this drives a large fraction of the gas into the center of the galaxy as shown in Figure 2. In our first three simulations, we found that $\sim$90%, 80% and 40% of the gas is driven to the center within 3 Gyrs. In the first two cases, half of the mass is transferred in an interval of 100-200 Myr.

We note one last problem in making detailed comparisons to observations. We link the collisional deformation of a galaxy to the channeling of gas into the middle of the galaxy. The response to the jolt of a high speed fly-by encounter occurs over the galaxy's internal orbital time, $\gtrsim$ 200 Myr (for a half light radius of 5.6 kpc and circular velocity of 160km s^{-1}). The three dimensional velocity dispersion in the cluster is $\sim 1,700$km s^{-1}, so each galaxy moves $\sim$ 400 kpc through the cluster as it responds to their encounter. Therefore, one can determine neither the galaxy that stimulated the encounter nor the location where the encounter occurred.

We haven't included star formation in our gas dynamical simulations, a weakness that we share with all past models of quasar fueling by gas in galaxies. The lack of star formation enables the gas to radiate the random energy resulting from the impulsive torques that diminish its angular momentum. If the material were all instantly turned into stars, it would not continue its inward flow and the central source would be extinguished. This caveat applies to all other models that use gas dyanmical simulations such as feuling with mergers (*cf.* Hernquist). However, we offer some observational evidence that the material does remain gas for a fairly long time.

In an accompanying paper (Moore, Lake and Katz 1997), we examine the remnants and compare them to spheroidal galaxies. We will examine the possibility of "black hole hunting" in nucleated spheroidals in the next section.

3. Predictions

Galaxy harassment only occurs in clusters where the impact velocities are too large to permit merging. By invoking this process to explain the qso hosts below L_*, we make four clear predictions that will each be explored in the next sections:

- quasars with low luminosity hosts should be in clusters where harassment occurs,
- resolved hosts should appear disturbed,
- regions where harassment is ongoing should show an enhanced quasar frequency
- black holes should exist in some nucleated spheroidal galaxies

3.1. The Environment of the BKS95 sample

Early studies of the environments of quasars concluded that they were not in rich clusters (Roberts, O'Dell and Burbidge 1977, Stockton 1978, French and Gunn 1983). That picture has changed and it is now clear that many low redshift quasars are in rich clusters. The majority of these may lie at the edge of the cluster (Oemler, Gunn and Oke 1972, Green and Yee 1984, Yee *et al.* 1989), but there are a few such as H 1821+643 (Schneider *et al.* 1992) and 3C 206 (Yee *et al.* 1989) that appear to lie at the center. Many other quasars show excesses of close optical companions (Hutchings, Crampton and Campbell 1984, Dahari 1984, Heckman *et al.* 1984 and Yee 1986). Heckman *et al.* (1984) obtained redshifts for 15 optical companions and found that 14 out of 15 were physical companions not projections.

Several groups have found that the clustering properties of quasars change rapidly with redshift. YMP93 find that quasars with redshifts $z \gtrsim 0.3$ occur in Abell richness class 0-1 clusters of galaxies, an environment that is roughly three times richer than that of the lower redshift quasars. YE93 reach a similar conclusion, but place the redshift break slightly higher ($z \gtrsim 0.6$). Fisher *et al.* (1996; hereafter FBKS) looked at a sample of ($z \lesssim 0.3$) with a mean redshift of ~ 0.2. They conclude that the quasars reside in stuctures that have at least half as many members as richness class R=0 Abell clusters. So, there seems to be a smooth trend with redshift.

These results agree qualitatively with our model, where the chaos of galaxy formation remains the reason for the observed peak of quasar number densities at a redshift of 2 and merging could dominate at the present day. In the standard hierarchical clustering model, Kaufman (1995) has shown that the infall rate of field galaxies into clusters peaks at redshifts of 0.3–0.5. At these redshifts, infalling galaxies are harassed to produce the central gas flow needed to create a quasar.

The real test will be a measurement of the evolution of the galaxy–galaxy and quasar–galaxy correlation functions to $z \sim 0.6$.

We can also examine what is known about the environments of the quasars in the BKS95 sample. BKS95 found 7 companions within 25 kpc of their targets, whereas they estimate the chance occurrence should be 0.375 per target. We found a wealth of other information on the environments of these quasars.

PG 0953+414: This is one of the richest environments in the Green and Yee (1984) sample. They see 25 galaxies in their field of 140" (a radius of 1 Mpc centered on the quasar at $z = 0.234$). BKS95 detect one companion, there are none evident on the H-band image of McLeod and Rieke (1994, hereafter McR).

PG 1116+215: This quasar lies at the edge of a relatively rich cluster discovered by Green and Yee (1984a) and studied by Ellingson, Green and Yee (1991). BKS95 found one companion within 25 kpc.

PG 1202+281: BKS95 find two companions. There is a bright companion that can be clearly seen on McR's H-band image. We found no studies of it's broader environment.

3C 273: BKS95 detect a host with a brightness that is greater than L_*, but they see no companions. McR see the jet to NW in their H-band frame and a second feature that is just S of W. Stockton (1980) found four galaxies within 250 kpc with velocity differences of -80, 300, 530, and 510 km s^{-1}. This quasar is probably in a poor cluster.

PKS 1302-102: BKS95 found two companions within 25 kpc. The limit set by BKS95 was just 0.4 magnitudes fainter than L_*. This quasar was also observed by Disney *et al.* (1995) who detected a host galaxy using a different filter and detector (the Faint Object Camera rather than the Wide Field/Planetary Camera). When they apply a standard color correction for the elliptical galaxy they detected, they find their detected galaxy is 0.2 magnitudes fainter than the BKS95 limit. This galaxy has been included in several studies of the environments of quasars. Green and Yee (1984) find 10 galaxies on their 140" field frames. Its cross-correlation with galaxy counts is typical of an Abell richness class 0 cluster, but the significance of the cross-correlation is marginal (Yates, Miller and Peacock 1989, Yee and Ellingson 1993).

PG 1307+085: BKS95 did not detect any companions within 25 kpc, but Yee (1987) found one that is just 41 kpc away. The H-band image of McR shows two patches of luminosity that are offset from the position of the quasar.

PG 1444+07: BKS95 detected a host galaxy with a magnitude of L_*. It appears to have a bar and ring. The H-band image in McR shows luminosity that is offset from the QSO. This is the only quasar in the BKS95 sample that was included in Green and Yee's (1984) sample, but no rich cluster was found.

3C323.1: Oemler, Gunn and Oke (1972) declare that this is "A QSO in a Rich Cluster of Galaxies".

It lies 6.5 arcmin from the center of a compact Zwicky cluster. This is slightly less than 1 Abell radius. BKS95 find a companion 6.9 kpc away that was previously found by Stockton (1982) to have a velocity difference with respect to the QSO of $\sim$150 km s^{-1}. Three companions can be seen on McR's H-band image.

In summary, three of the quasars are known to live in rich clusters of galaxies: PG 0953+414, PG 1116+215, and 3C323.1. A fourth (PKS 1302-102) appears to be in a cluster, but the evidence is marginal. The only quasars that have deep wide field images and do not appear to be in clusters have hosts that are $\sim L_*$. The galaxy host of 3C273 is brighter than L_* and it is found in an environment that might be more conducive to merging than harassment (the velocity dispersion appears to be less than 500 km s^{-1}). The only quasar in the Green and Yee (1984) survey that does not appear to be in a cluster, PG 1444+407, has the second most luminous host ($\sim L_*$) in the BKS95 sample.

More recently, BKSS97 completed a study of 20 quasar hosts. In the original BKS95 sample, half of the quasars had reshifts between 0.239 and 0.236. While the newer sample is 2.5 times larger, it added only 2 more galaxies to the redshift range where we expect harassment to become important. Examining the two new quasars in this range, one is observed to be interacting (0316-416) and the other is an elliptical (PG1004+130).

3.2. Characteristics of the Candidate Host Galaxies

BKS95 only found candidate hosts for the 3 QSOs: PG 1116+215, 3C 273 and PG 1444+407. Only the host of 3C 273 is clearly as bright as L_* and it appears to be an elliptical slightly offset from the position of the QSO. The hosts of the other two galaxies are about a half magnitude fainter than L_* when BKS95 use aperture magnitudes and slightly brighter than L_* if they employ an exponential disk model. The PG 1116+215 host appears to have partial rings while the PG 1444+407 host appears to have a bar and a ring-like structure. Having failed to confirm past detections of QSO hosts, BKS95 are circumspect in their descriptions of their images. However, we are encouraged by the structures described for the two less luminous hosts. Strong bars and rings are often seen in harassed galaxies.

3.3. Are Quasars More Frequent Where Galaxies Are Being Harassed?

The phenomena of galaxy harassment was discovered in our study of the destruction of substructure in mergers (MKL96b). In Moore *et al.* (1996), we first applied it to explain the evolution of cluster populations discovered by Butcher and Oemler (1978). Harassment is clearly occurring in these clusters. If this is the cause of nuclear activity in quasars found in sub-L_* galaxies, then we expect that the frequency of AGNs should be higher in clusters at $z \sim 0.3 - 0.5$ that show the Butcher-Oemler effect.

We find the data to check this prediction to be extremely puzzling. When they first embarked on their decade long spectroscopic study of these clusters, Dressler and Gunn (1982, 1983, see also Dressler 1987) reported that the frequency of AGNs in these clusters was much higher than the 1% found in $z = 0$ clusters (Dressler, Thompson and Shectman 1985). A high fraction of AGNs was confirmed by Lavery and Henry (1989), but Couch and Sharpless (1985) found that only 1 in 112 of the blue galaxies they examined were AGNs.

We find no clear consensus on this issue and this remains a testable prediction of the model. We do note that our first and third predictions have some redundancy. Quasars at intermediate redshifts could not lie in clusters rich enough to be classified by Abell (Yates, Miller and Peacock 1989, and Yee and Ellingson 1993) if nuclear activity is not enhanced in clusters.

3.4. Are there black holes in nucleated spheroidals?

With sensible assumptions about their duty cycle, the dead remnants of quasars are inferred to have number densities comparable to galaxies brighter than L_* (c.f. Haehelt and Rees 1993 and references therein). This has stimulated a search for massive objects in the centers of bright galaxies (c.f. Kormendy and Richstone 1996). Our candidate hosts have a much greater spatial frequency and are associated with quasars at lower redshifts where they are relatively rare. Hence, a tiny fraction of the spheroidals are expected to have massive nuclei. However, the low velocity dispersions of the spheroidal galaxies should make it easier to detect dark matter in their cores. Peterson and Caldwell (1993) and Nieto *et al.* (1990) have conducted the largest studies of spheroidals and dwarf ellipticals. All together, there are fewer than two dozen galaxies. Of these, NGC 4486B (Nieto *et al.* 1990) is one of the most unusual. It has an absolute magnitude, $M_B = -17.4$, but its central velocity dispersion is measured to be 194 ± 6, falling to 170 ± 7 when averaged over its half light radius. It's mass-to-light ratio, is on the high end, $M/L \sim 7$, but hardly extreme. The detection of low level nuclear activity in spheroidals would also be of great interest.

4. Conclusion

Recent HST results have challenged the conventional picture that quasars are associated with high luminosity hosts. We have presented a model— galaxy harassment—that rapidly channels gas into the centers of low luminosity hosts. This model has several predictions. We find evidence that most if not all of the quasars with sub-L_* hosts are in the high density environments that lead to harassment. The HST images of host candidates by BKS95 shows tantalizing evidence of the distortions associated with harassment. In attempting to test the prediction of a higher frequency of AGNs in Butcher-Oemler clusters, we find some support amidst active controversy.

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REFERENCES

Bahcall, J. N. Kirhakos, S., Saxe, D. H. and Schneider, D. P. 1995, ApJ, 479, 642 (BKSS97)

Bahcall, J. N. Kirhakos, S. and Schneider, D. P. 1995, ApJ, 450, 486 (BKS95)

Bender, R. and Nieto, J.-L. 1990, A&A, 239, 97

Butcher, H. and Oemler, A. 1978, ApJ, 219, 18

Couch, W. and Sharples, R.M. 1987, MNRAS, 229, 422

Dahari, O. 1984, AJ, 89, 966

Disney, M. *et al.* , 1995, Nature, 376, 150

Dressler, A. and Gunn, J. E. 1982, ApJ, 263, 533

Dressler, A. and Gunn, J. E. 1983, ApJ, 270, 7

Dressler, A. 1987, Nearly Normal Galaxies : from the Planck Time to the Present, S. M. Faber, New York : Springer-Verlag, 265

Dressler, A., Thompson, I.B. and Shectman, S.A. 1985, ApJ, 288, 481.

Fisher, J. R. and Tully, B. 1981 Astron. Ap. Suppl., 47, 139

French, H.B and Gunn, J.E. 1983, ApJ, 270, 7

Hutchings, J. B., Crampton, D. and Campbell, B. 1984, ApJ, 280, 41

Kormendy, J. and Richstone, D., 1996, Anual Rev. Astr. Astro., 33, 581

Ellingson, E., Green, R. F. and Yee, H. K. C. 1991, ApJ, 378, 476

Fisher, K. B., Bahcall, J. N., Kirhakos, S. and Schneider, D. P. 1996, ApJ, submitted.

Green, R. F. and Yee, H. K. C. 1994, ApJS, 54, 495

Haehnelt, M.G. and Rees, M.J. 1993, MNRAS, 263 168.

Heckman, T. M., Bothun, G. D., Balick, B. and Smith, E.P. 1984, AJ, 89, 958

Hernquist, L. 1989, Nature, 340, 687

Hernquist, L. and Katz, N. 1989, ApJS, 70, 419

Katz, N., Weinberg, D. and Hernquist, L. 1996, ApJS, 105, 19

Kauffmann, G. 1995, MNRAS, 274, 153

Le Fèvre, O., Hudon, D., Lilly, S.J., Crampton, D., Hammer, F. and Tresse, L. 1996, ApJ, 461, 534

Lavery, R.J. and Henry, P. 1988, ApJ, 330, 596

McLeod, K. K. and Rieke, G. H. 1994, ApJ, 431, 137

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

Moore, B., Katz, N. and Lake, G., 1996, ApJ, 457, 455 (MKL96b)

Moore, B., Lake, G. and Katz, N. 1997, ApJ, this volume

Nieto, J.L, Davoust, E., Bender R., and Prugniel, P. 1990, Astron.Astro., 230, 17

Oemler, A., Gunn, J. E. and Oke, J. B. 1972, ApJ, 176, L47.

Peterson, R. C. and Caldwell, N. 1993, AJ, 105, 1411.

Schechter, P. L. 1976, ApJ, 203, 297

Schneider, D. P., Bahcall, J. N., Gunn, J. E. and Dressler, A. 1992, AJ103, 1047

Stockton, A. 1980, Objects of High Redshift, G.O. Abell and P. J. E. Peebles, Dordrecht: Reidel, 133

Stockton, A. 1982, ApJ, 257, 33

Toomre, A. 1964 ApJ, 139, 1217

Van Der Marel, R.P., 1991, MNRAS, 253, 710

White, S.D.M., and Rees, M. 1978, MNRAS, 183, 341

Yates, M. G., Miller, L. and Peacock, J. A., MNRAS, 240, 129

Yee, H. K. C. 1987, Observational Evidence of Activity in Galaxies, E. Ye. Khachickian, K. J. Fricke and J. Melnick, Dordrecht: Reidel, 363.

Yee, H. K. C. and Green, R. F. 1991, ApJ, 280, 79

Yee, H. K. C., Ellingson, E., Green, R. F. and Prichet, C. J. 1989, The Epoch of Galaxy Formation, C. S. Frenk *et al.* , Dordrecht: Kluwer, 185.

Yee, H. K. C. and Ellingson, E. 1993 ApJ, 411, 43

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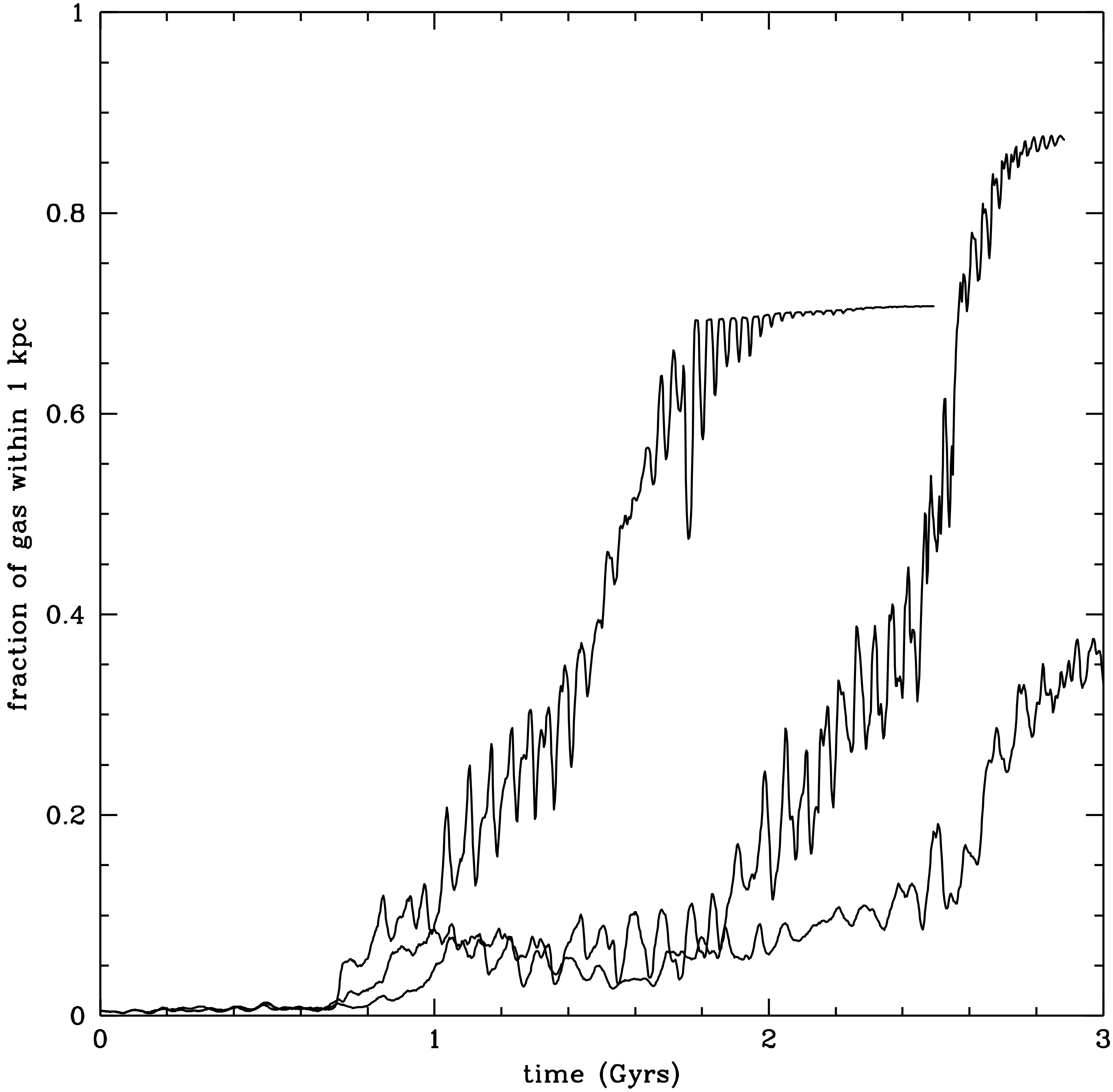
Figure Captions

Figure 1 Snapshots of the evolution of the gas disk in one of the harassed galaxies that we simulated. The full time evolution can be seen in the last segment of the video. The disk shown is the one where 90% of the gas is transported into the central kpc (see Figure 2).

Figure 2 The time evolution of the fraction of gas that lies within 1 kpc of the center of the galaxy. On average, more than half of the gas lies within this radius within a few Gyr—in one of the three cases, 90% of the gas is in the center. In the two cases where the most mass is pushed into the center, about half of it is transferred during an interval of just 100-200 Myr.



fraction of gas within 1 kpc
1
0.8
0.6
0.4
0.2
0
0
1
2
3
time (Gyrs)