

# Simulated Versus Observed Cluster Eccentricity Evolution

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## ABSTRACT

The rate of galaxy cluster eccentricity evolution is useful in understanding large scale structure. Rapid evolution for  $z < 0.13$  has been found in two different observed cluster samples. We present an analysis of projections of 41 clusters produced in hydrodynamic simulations augmented with radiative cooling and 43 clusters from adiabatic simulations. This new, larger set of simulated clusters strengthens the claims of previous eccentricity studies. We find very slow evolution in simulated clusters, significantly different from the reported rates of observational eccentricity evolution. We estimate the rate of change of eccentricity with redshift and compare the rates between simulated and observed clusters. We also use a variable aperture radius to compute the eccentricity,  $r_{200}$ . This method is much more robust than the fixed aperture radius used in previous studies. Apparently radiative cooling does not change cluster morphology on scales large enough to alter eccentricity. The discrepancy between simulated and observed cluster eccentricity remains. Observational bias or incomplete physics in simulations must be present to produce halos that evolve so differently.

*Subject headings:* cosmology: galaxy clusters: evolution – large-scale structure of universe – methods: numerical

## 1. Introduction

One would expect eccentricity evolution of an isolated galaxy cluster due to violent relaxation of the system (Aarseth & Binney 1978). It has been proposed (Melott et al. 2001, Plionis 2002) that one can put constraints on  $\Omega_m$  by measuring the rate of morphological changes in clusters. Eccentricity can measure these changes since it is usually measured on the outer regions of clusters.

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Melott, Chambers, and Miller (2001, hereafter MCM) reviewed five observational cluster data sets (three optical and two X-ray) and found evolution in each case with varying significance. Plionis (2002, hereafter PL02) also found significant evolution in cluster eccentricity in the optical APM cluster catalog. Recently, Floor et al. (2003, hereafter FMMB) presented findings that showed much slower evolution of eccentricity in simulated clusters. It is possible that the addition of radiative cooling might produce simulated clusters that better emulate observed clusters. The hydrodynamic simulations presented in FMMB have now been outfitted to include radiative cooling (see Motl et al. 2003). We also have a larger sample of simulated clusters which improves our statistics greatly.

Galaxy clusters are potentially useful for studying the nonlinear growth of density perturbations. Eccentricity measurements of clusters aid in understanding the growth of clusters and large scale structure. Our procedure emphasizes the outer regions of clusters and is not particularly sensitive to small scale changes in cluster core density. For this reason, eccentricity evolution provides a means to measure changes in cluster morphology on the largest scales. Also, eccentricity presents a valuable tool to observational cosmology since loss of data on small scales will not drastically affect the measured value.

The question posed is whether radiative cooling will reduce the disagreement between simulated and observed cluster eccentricity. Cooling of the central gas of a cluster would cause contraction followed by deepening of the central potential well. This could cause dark matter to preferentially reside in the center yielding a lower eccentricity over time. Therefore, one might expect the introduction of radiative cooling to increase the rate of simulated eccentricity evolution. However, if the change in morphology due to cooling is on small scales then this might not affect the eccentricity of the outer regions, since the cooling time at the outer regions of clusters is long. The cooling time in the core of clusters is small which causes a collapse of the region. Since the outer regions are hydrostatically supported by the inner regions one would expect that cooling in the center could cause baryonic infall. This moving gas will perturb the dark matter potential which could cause extra-core morphology changes. Regardless of the effects of cooling on individual clusters, when mergers take place the accreted substructure can change significantly when cooling is applied (Motl et al. 2003). For these and pedagogical reasons an investigation of the effects of radiative cooling on galaxy cluster eccentricity evolution is presented.

The paper proceeds as follows: in §2 we discuss the simulations used to produce our result. The method of eccentricity computation is discussed in §3. The results and discussion are in §4 and §5, respectively. Acknowledgments are listed in §6.

## 2. Simulations

There were two sets of simulations used in FMFB. One is an N-Body code with only dark matter which of course has no radiative cooling. The hydrodynamic simulations being analyzed here were conducted with a coupled Adaptive Mesh Refinement Eulerian hydrodynamics & N-body code (Norman & Bryan 1999, Bryan, Abel & Norman 2000). The baryonic fluid is evolved with the Piecewise Parabolic Method (Colella & Woodward 1984) and the dark matter particle potential is calculated with an adaptive particle mesh scheme using the second-order accurate TSC interpolation. Each individual cluster simulation evolves the same cosmological volume (with box length 256 Mpc) with periodic boundary conditions and deploys the adaptive mesh infrastructure about a different region of interest. Each cluster region is statically refined by two nested grids and within the innermost static subgrid, further subgrids are created as needed to track collapsing regions. The dark matter particles exist on the three static grids and have a peak mass resolution of  $1.3 \times 10^{10} M_{\odot}$ . For the calculations presented here, each subgrid is refined by a factor of two compared to its parent and we allow up to seven levels of refinement yielding a peak spatial resolution of 16 kpc.

We use a flat  $\Lambda$ CDM cosmology with the following parameters:  $\Omega_b = 0.026$ ,  $\Omega_m = 0.3$  and  $\Omega_{\Lambda} = 0.7$  and we assume a Hubble constant  $H_0 = h \text{ 100 km s}^{-1} \text{ Mpc}^{-1}$  with  $h = 0.7$ . Our initial conditions are generated with the Eisenstein & Hu (1999) form for the CDM power spectrum and we use a normalization of  $\sigma_8 = 0.93$ . The two samples of numerical clusters presented here derive from the same initial conditions and cosmological model and differ only in that for one sample the baryonic fluid is allowed to lose energy to radiation and cool. The adiabatic sample will be known as  $\Lambda$ CDMH and the cooled sample as  $\Lambda$ CDMRC. We use a tabulated cooling curve for a plasma of fixed metal abundance of 0.3 solar and the cooling curve is truncated at a minimum temperature of  $10^4 K$  (Westbury & Henriksen 1992). For the present work we neglect the effects of thermal conduction as well as star formation and supernova feedback.

We have investigated the morphological effects of radiative cooling on the  $\Lambda$ CDMH simulations. For a complete description of radiative cooling see Motl et al. (2003). We used clusters that were isolated using the ‘‘HOP’’ algorithm (Eisenstein & Hut 1998). This algorithm is based on overdensities and will select all regions above some threshold density and then merges them based on other considerations. The full procedure is discussed in FMFB and Eisenstein & Hut (1998) but note that we used the following parameter set:  $\delta_{peak} = 480$ ,  $\delta_{saddle} = 400$ , and  $\delta_{outer} = 160$ . Clusters were detected in three-dimensional space while analysis will be done in two-dimensional projection. We chose to analyze only the most massive clusters in this simulation. Due to the large volume of the simulated region ( $256^3 \text{ Mpc}^3$ ) all clusters detected in this fashion were richness  $R \geq 2$ . However, FMFB used

clusters richness  $R \geq 1$  so conclusions from these data seem to be richness independent.

Simultaneously, a larger set of the  $\Lambda$ CDMH simulations than available to FMMB were prepared and made available for analysis. In FMMB the results of eleven analyzed clusters were presented. Here, thirty more projected clusters were simulated using the same parameters. This gives us much better statistics than in FMMB.

### 3. Measuring Eccentricity

Due to widely varying definitions of ellipticity ( $\epsilon$ ) we chose instead to use the mathematically defined term eccentricity. For an ellipse with major axis  $a$  and minor axis  $b$ , the eccentricity ( $e$ ) is defined to be

$$e = \sqrt{1 - \frac{b^2}{a^2}} \quad (1)$$

All results are presented in terms of  $e$ . Note that some authors use this formula to define ellipticity, resulting in some of the ambiguity of the term.

Since we are using three-dimensional simulations it would be possible to measure three-dimensional features of the isolated clusters. However, to better emulate observed results we chose to analyze the clusters in projection. Therefore, three projections of each cluster were made, one along each Cartesian axis. Jing & Suto (2002) discuss a robust triaxial halo morphology measurement technique. This method works well but the halos are identified in three dimensions. This was not possible in the observational data used here; moreover a method of applying the triaxial halo analysis to observational data is not presented in Jing & Suto (2002). Lee & Suto (2004) present a deprojection technique based on Sunyaev-Zel'dovich or X-ray observational data. This method is however reliant on a five-parameter fit and commonly results in errors of 20 percent or higher. It is doubtful that any benefit in accuracy in eccentricity computation could be garnished given that the inertia tensor method is not wildly inaccurate. A full study should be conducted regarding the difference in eccentricity of projected clusters using the inertia tensor method presented here with deprojected 2D clusters using the method of Lee & Suto (2004). However, since the observational data used in MCM and PL02 come from both optical and X-ray sources it is impossible to deproject them all and the triaxial halo method is therefore discounted.

To compare with previous observational studies we analyze both projected dark matter and simulated projected X-ray emissions. We create synthetic X-ray images by projecting the calculated X-ray emission (both line and free-free emission) from the gas assuming a metal abundance of 0.3 relative to solar and in an energy band extending from 0.5 to 2.0 keV.

We assume that the dark matter halos are representative of the observed optical emissions. This can be justified by noting that optical emissions come primarily from galaxies which are approximately collisionless bodies. The relaxation of galaxies and dark matter is therefore assumed to be similar. White et al. (1993) discuss the distribution of baryonic matter in galaxy clusters. They determine that the baryon fraction only deviates significantly from the cosmological baryon fraction near the core of clusters. This implies that for the remainder of the cluster, the region where our aggregate measures are being conducted, the baryonic fraction is comparable to the cosmological value. Additionally, Mellier (1999) reviews many studies where weak lensing is used to show that the dark matter distribution in galaxy clusters is similar to both the optical and X-ray emission distributions. This is only true if the  $n^2$  dependence of X-ray emissions are taken into account.

We identify the cluster center as the center of mass of the objects produced by the group finding algorithm. A common substitute for the center of mass is to choose the highest luminosity pixel of an image. Here this would correspond to the highest density point in the cluster, assuming that luminosity  $\propto$  density. This procedure was implemented to see if it affects the measured eccentricities. The change in eccentricity was rarely larger than the standard deviation of the sample. We continue to use the center of mass because it is more easily specified and more robust to variation in observational details.

A brief study was conducted to determine the typical displacement of the highest density peak is from the center of mass. The highest density peak was determined by first rebinning the projected clusters into larger bins to remove statistical fluctuations. The bins were selected such that one side is approximately 100 kpc (at  $z = 0.1$ ), or comparable resolution to X-ray surveys. The center of the bin with the highest density was noted. It is assumed that this point would be analogous to the highest luminosity point of an observed cluster. The mean separation between the center of mass and density peak was 0.32 Mpc with  $\sigma_{sep} = 0.37$  Mpc. The separation of the two is quite erratic; often if the cluster has significant substructure the highest density point will occur in an outlier of the cluster while the center of mass is closer to the center of the projected region. This study was conducted using the dark matter density as a measure. Observational studies obviously cannot use the dark matter density so another brief study was conducted. The brightest X-ray pixel was discovered using the same methodology as above. The X-ray luminosity appears to locate the dark matter center of mass somewhat better than either the highest density dark matter or baryonic pixel. When the dark matter center of mass was compared to the brightest X-ray pixel the mean separation was 0.30 with  $\sigma_{sep} = 0.25$  Mpc. We therefore advocate using the brightest X-ray pixel as the center of an image rather than the brightest optical pixel, when both are available.

Once the cluster center is determined, we emulated procedures used in the studies discussed in MCM and PL02. A circle of radius  $r_{outer} = 1.5 \text{ h}^{-1} \text{ Mpc}$  is drawn about the cluster center. This circle is commonly referred to as the aperture radius. The mass of the material inside the aperture radius is then determined. An inner circle is then drawn such that twenty percent of the mass is contained in the annulus. It was the eccentricity of this annulus that was measured. See FMMB for a brief discussion of this method as compared to others. We also used the virial radius,  $r_{200}$  as the aperture radius. This radius is defined to be the radius of a circle in which the density is 200 times the background density of the simulation. In this case it was always computed in two dimensions, though it could in principle be done in three. Results using this as the aperture radius are presented along with the fixed radius.

Once the annulus is isolated, the moment of inertia about the cluster center is computed. It is only the material that is inside the annulus that is used to compute the moment of inertia. The eigenvalues of the moment of inertia tensor are proportional to the square of the object’s axes. We therefore measure the eccentricity as follows:

$$e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}} \quad (2)$$

with  $\lambda_1 < \lambda_2$ . This method’s correctness is subject to its application to a homogeneous ellipse. Obviously, clusters are not entirely homogeneous objects but this is the best known method of determining the eccentricity.

## 4. Results

In Table 1 the results for the  $\Lambda$ CDMH simulations are presented. Table 2 is analogous except for the slightly smaller size data set of the  $\Lambda$ CDMRC simulations. For each cluster we show the median, mean, and standard deviation in the mean ( $\sigma_e$ ) of the eccentricity. Inspection of tables 1-4 and their corresponding  $\sigma_e$  values will reveal that they are nearly identical. Tables 3 and 4 display the same information as 1 and 2 except using  $r_{200}$  as  $r_{outer}$ . Table 5 presents calculated slopes ( $de/dz$ ) for both the simulational and observational data sets. The slopes and errors ( $\sigma_s$ ) were calculated using a least squares algorithm. The observational data sets are described in either MCM or PL02 as indicated. While all slopes indicated are larger than zero, the observational slopes are always much larger. Before the observational slopes were calculated the ellipticities ( $\epsilon$ ) were converted to eccentricities. The standard definition of  $\epsilon$

$$\epsilon = 1 - \frac{b}{a} \quad (3)$$

with  $a$  and  $b$  as defined previously. Both MCM and PL02 reported results in this form.

Note that in every case presented the data has some positive slope. The observational data has a slope close to one while simulational slope is always much less than one. This supports the conclusion seen in FMMB: simulated clusters evolve slower than observed clusters. This result was checked with the recalculation of eccentricity subject to  $r_{outer} = r_{200}$ . Despite a reduction in eccentricity for all simulated clusters, the rate of evolution remains unchanged. It seems that the  $r_{outer}$  choice was not the source of the discrepancy.

## 5. Discussion

As discussed in FMMB we checked our conclusions by varying many parameters related to these simulations. We varied the value of  $\sigma_8$ , the random seed for density perturbations, the cluster detection algorithm and its parameters, the presence and magnitude of a cosmological constant, and others. We have now also explored the influence of radiative cooling, changing the aperture radius, and the definition of the center of a cluster. None of these alterations drastically changed the results from previous eccentricity studies. Changing the aperture radius reduced the inter-simulation discrepancy. However, the rate of evolution remains significantly slower in simulated clusters than in observed ones, even with the introduction of radiative cooling in the simulations. We discuss here the inter-simulation disagreement, the disagreement between observation and simulation, possible sources of error, and future work that may aid in understanding this problem.

Using  $r_{200}$  as the aperture radius significantly reduced the inter-simulation eccentricity difference. We propose that this value be used for the aperture radius in future studies since it is not difficult to compute and produces more physically correct results. When working with simulations it is quite easy to compute numerically in projection or otherwise. Alternately, observational studies can use the analytic result presented in Navarro, Frenk, and White (1997). While  $r_{200}$  is not precise it does reflect the variation between clusters of different mass and allows for a more consistent measurement of eccentricity.

There are two main differences noticed between simulated and observed clusters. The first is the actual measured eccentricity. In simulated clusters the average eccentricity is about 0.6 or higher which is 0.37 in ellipticity. Observed clusters at  $z \approx 0.05$  have ellipticities of around 0.3, suggesting that present day clusters would have lower eccentricity than the predicted present day simulated clusters. Therefore, lack of evolution notwithstanding, there is a problem with simulated cluster morphology. The greater discrepancy is the rate of eccentricity evolution as presented in FMMB. Radiative cooling did not significantly

Table 1.  $\Lambda$ CDMH Cluster Eccentricities,  $N=129$ ,  $R > 2$

Simulation type	$\sigma_8$	Redshift	Median $e$	Mean $e$	$\sigma_e(\text{mean})$
$\Lambda$ CDMH (mass)	0.93	0.	.65	.63	.012
$\Lambda$ CDMH (mass)	–	0.1	.67	.67	.012
$\Lambda$ CDMH (mass)	–	0.25	.72	.70	.012
$\Lambda$ CDMH (X-ray)	0.93	0.	.65	.66	.015
$\Lambda$ CDMH (X-ray)	–	0.1	.71	.70	.016
$\Lambda$ CDMH (X-ray)	–	0.25	.73	.72	.015

Table 2.  $\Lambda$ CDMRC Cluster Eccentricities,  $N=123$ ,  $R > 2$

Simulation type	$\sigma_8$	Redshift	Median $e$	Mean $e$	$\sigma_e(\text{mean})$
$\Lambda$ CDMRC (mass)	0.93	0.	.67	.64	.012
$\Lambda$ CDMRC (mass)	–	0.1	.69	.68	.012
$\Lambda$ CDMRC (mass)	–	0.25	.70	.69	.012
$\Lambda$ CDMRC (X-ray)	0.93	0.	.67	.68	.016
$\Lambda$ CDMRC (X-ray)	–	0.1	.73	.71	.015
$\Lambda$ CDMRC (X-ray)	–	0.25	.74	.73	.015



Table 3.  $\Lambda$ CDMH Cluster Eccentricities ( $r_{200}$ ),  $N=129$ ,  $R > 2$

Simulation type	$\sigma_8$	Redshift	Median $e$	Mean $e$	$\sigma_e(\text{mean})$
$\Lambda$ CDMH (mass)	0.93	0.	.61	.60	.012
$\Lambda$ CDMH (mass)	–	0.1	.64	.64	.011
$\Lambda$ CDMH (mass)	–	0.25	.68	.66	.012
$\Lambda$ CDMH (X-ray)	0.93	0.	.65	.64	.015
$\Lambda$ CDMH (X-ray)	–	0.1	.64	.63	.015
$\Lambda$ CDMH (X-ray)	–	0.25	.69	.68	.015

Table 4.  $\Lambda$ CDMRC Cluster Eccentricities ( $r_{200}$ ),  $N=123$ ,  $R > 2$

Simulation type	$\sigma_8$	Redshift	Median $e$	Mean $e$	$\sigma_e(\text{mean})$
$\Lambda$ CDMRC (mass)	0.93	0.	.63	.61	.012
$\Lambda$ CDMRC (mass)	–	0.1	.65	.63	.012
$\Lambda$ CDMRC (mass)	–	0.25	.68	.66	.012
$\Lambda$ CDMRC (X-ray)	0.93	0.	.67	.67	.016
$\Lambda$ CDMRC (X-ray)	–	0.1	.70	.70	.015
$\Lambda$ CDMRC (X-ray)	–	0.25	.67	.67	.015

change the rate of change of eccentricity. The change seen in  $de/dz$  in Table 5 suggests even slower evolution in a radiatively cooled simulation. Changing the aperture radius did not significantly change the eccentricity evolution of any sample. Either simulations are lacking critical physics which cause much faster cluster relaxation or observational cluster samples are missing either high eccentricity clusters at low  $z$  or low eccentricity clusters at high  $z$ .

We briefly discuss two physical processes currently being integrated into cosmological simulations that may help to alleviate this discrepancy, simulated star formation and thermal conduction. Simulated star formation (and subsequent supernovae) would tend to heat the gas inside the cluster. However, it is quite difficult to implement a simulation which has detail down to single-star levels and can simultaneously simulate a cosmological volume. Further, any morphological effects from star formation would be present at high  $z$  and result only in the production of a lower density core. It is doubtful that star formation would change the shape of clusters on large enough scales to alter the measured eccentricity significantly. See Bryan et al. (2001) for a complete description of a star formation model. Additionally, as suggested by Narayan and Medvedev (2001) and Medvedev et al. (2003), thermal conduction from the hot outside of the cluster to the center of the cluster can be critical to the X-ray emissions of a cluster. Loeb (2002) discusses that while conductivity may not be responsible for cooling core clusters, it can affect the temperature distribution in clusters. He shows that a large heat conduction coefficient leads to cooling of the cluster gas which transitively affects the intergalactic medium. These temperature changes outside the core could easily affect the X-ray morphology of clusters. Any flows via conductivity can affect the eccentricity of clusters over time since these flows involve the transfer of energy across a significant distance. Thermal conductivity should be added to simulations to better emulate reality but it is again doubtful that it will change the eccentricity significantly. There is no obvious missing physics which should drastically alter the morphology of simulated clusters.

Observational bias or incompleteness in the currently available cluster catalogs could also produce the observed discrepancy. MCM studies the ellipticity evolution in observational samples. The various samples were cut to only include those clusters which were members of the MX galaxy survey. Miller et al. (1999) have shown that this sample has few projection effects and that only  $\sim 5\%$  of clusters are spurious detections of overdensities on the sky. Additionally, the co-moving number density of these clusters is nearly constant to  $z = 0.1$ , indicating its level of completeness for systems  $R \geq 1$ . However, selection effects present in the various studies, both optical and X-ray, may have persisted in spite of this cut. Highly eccentric, low  $z$  clusters could be hard to identify using standard cluster detection algorithms due to their large spread on the sky. We turn to two new observational surveys which will hopefully add to the completeness of observational cluster catalogs.

We anticipate results from the SDSS (Nichol et al. 2000) which should be completed shortly. This catalog promises to be quite complete and, provided a proper algorithm is chosen for cluster detection, bias-free. We feel that the C4 algorithm discussed in Nichol et al. (2003) appears to be a non-biased cluster detection algorithm applied to a complete sample of galaxies. Assuming that optical emissions are a tracer of dark matter, a comparison between simulated dark matter density and optical emissions will possibly shed light on the presented discrepancy. Additionally, we look forward to a new cluster catalog derived from the XMM-Newton survey. XMM-Newton has good spatial resolution and excellent sensitivity (Arnaud et al. 2002) making it a good candidate for dim cluster measurements. Inclusion of these dim clusters could help the discrepancy presented. Simulated X-ray emission is well understood and is not subject to the assumption that it directly traces dark matter as optical emissions are. Other new X-ray surveys will also make this result more robust.

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## REFERENCES

- Aarseth, S.J. & Binney, J.J., 1978, MNRAS, 185, 227
- Arnaud, M., Majerowicz, S., Lumb, D., Neumann, D.M., Aghanim, N., Blanchard, A., Boer, M., Burke, D., Collins, C., Giard, M., Nevalainen, J., Nichol, R.C., Romer, K., Sadat, R., 2002, A&A, 390, 27
- Bryan, G.L., Abel, T., & Norman, M.L. 2001, Proceedings of Supercomputing 2001, <http://www.sc2001.org>
- Colella, P. & Woodward, P.R., 1984, J. Comput. Phys., 54, 174
- Eisenstein, D.J., & Hut, P., 1998, ApJ, 498, 137
- Eisenstein, D.J. & Hu, W., 1999, ApJ, 518, 2
- Floor, S.N., Melott, A.L., Miller, C.J., & Bryan, G.L., 2003, ApJ, 591, 741

- Jing, Y.P., Suto, Y., 2002, *ApJ*, 574, 538
- Lee, J., Suto, Y., 2004, *ApJ*, 601, 599
- Loeb, A., 2002, *New Astronomy*, 7, 279
- Medvedev, M.V., Melott, A.L., Miller, C.J., & Horner, D., 2003, *ApJ* submitted, astro-ph/0303310
- Mellier, Y., 1999, *ARA&A*, 37, 127
- Melott, A.L., Chambers, S.W., & Miller, C.J., 2001, *ApJ*, 559, L75
- Miller, C.J., Batuski, D.J., Slinglend, K., & Hill, J., 1999, *ApJ*, 523, 492
- Motl, P.M., Burns, J.O., Loken, C., Norman, M.L., Bryan, G.L., 2003, *ApJ*, in press
- Narayan, R., & Medvedev, M.V., 2001 *ApJ Letters*, 562, L129
- Navarro, J.F., Frenk, C.S., White, S.D.M., 1997, *ApJ*, 490, 493
- Nichol, R., Miller, C., Connolly, A., Chong, S., Genovese, C., Moore, A., Reichart, D., Schneider, J., Wasserman, L., Annis, J., Brinkman, J., Bohringer, H., Castander, F., Kim, R., McKay, T., Postman, M., Sheldon, E., Szapudi, I., Romer, K., Voges, W., 2000, *Proceedings of MPA/MPE/ESO Conference “Mining the Sky”*
- Nichol, R.C., Miller, C.J., Goto, T., 2003, *JENAM 2002 Workshop on “Galaxy Evolution in Groups and Clusters”* in press
- Norman, M.L. & Bryan, G.L., 1999 in *ASSL Vol. 240: Numerical Astrophysics*, eds. S.M. Miyama, K. Tomisaka, & T. Hanawa , (Boston: Kluwer), 19
- Plionis, M., 2002, *ApJ*, 572, L67
- Westbury, C.F. & Henriksen, R.N., 1992, *ApJ*, 338, 64
- White, S.D.M., Navarro, J.F., Evrard, A.E., & Frenk, C.S., 1993, *Nature*, 366, 429

Table 5. Summary of Eccentricity Evolution for Observational and Simulated Data

Data Set (Paper Source)	$\frac{de}{dz}$	$\sigma_s$	$N$
Optical (MCM & PL02)	1.07	0.14	497
X-ray (MCM)	1.13	0.48	48
Adiabatic Hydrodynamic Sim DM	0.27	0.07	387
Adiabatic Hydrodynamic Sim X-ray	0.24	0.09	387
Cooled Hydrodynamic Sim DM	0.19	0.07	369
Cooled Hydrodynamic Sim X-ray	0.18	0.09	369
CDM N-Body Sim (FMFB low $\Omega$ )	0.56	0.13	162