

The Velocity Dispersion of MS1054–03: A Massive Galaxy Cluster at High Redshift¹

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ABSTRACT

We present results from a dynamical study of the high redshift, massive, X-ray luminous galaxy cluster MS1054–03. We significantly increase the number of confirmed cluster members by adding 20 to an existing set of twelve; using the confirmed members, we estimate MS1054–03’s redshift, velocity dispersion, and mass. We find that $z = 0.8329 \pm 0.0017$, $\sigma = 1170 \pm 150$ km/s, and the central mass is approximately $1.9 \pm 0.5 \times 10^{15} h^{-1} M_{\odot}$ (within $R = 1 h^{-1}$ Mpc; $H_0 = 100 h$ km s⁻¹ Mpc⁻¹, $q_0 = 0.5$). MS1054–03 is one of a handful of high redshift ($z > 0.5$) clusters known that also has X-ray and weak-lensing observations (Donahue et al. 1998; Luppino & Kaiser 1997); we find our dynamical mass agrees with mass estimates from both studies. The confirmation of MS1054–03 as a massive cluster at $z \sim 0.8$ is consistent with an open ($\Omega_M \sim 0.3$) or flat, Λ -dominated ($\Omega_M + \Omega_{\Lambda} = 1$) universe. In addition, we compare MS1054–03’s velocity dispersion and X-ray temperature to a sample of low and intermediate redshift galaxy clusters to test for evolution in the $\sigma - T_x$ relation; we find no evidence for evolution in this relation to $z \sim 0.8$.

Subject headings: cosmology: observations — galaxies: clusters: individual (MS 1054–0321) — large scale structure of universe

¹Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

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1. Introduction

With the advent of large telescopes and X-ray surveys (e.g. *Einstein* Medium Sensitivity Survey, ROSAT North Ecliptic Pole Survey), the study of high redshift ($z > 0.5$) galaxy clusters has evolved into a field rich with multi-wavelength observations (Gioia & Luppino 1994; Fukazawa et al. 1994; Carlberg et al. 1996; Donahue 1996; Donahue et al. 1998). Forming at the junction of walls and filaments (Kang et al. 1994; Cen & Ostriker 1994), clusters represent the extreme end of fluctuations in the primordial power spectrum and may place strong constraints on cosmological models (Eke et al. 1998; Gioia 1998). On a smaller scale, the cluster environment provides an useful laboratory for studying galaxy evolution in a range of different local densities. While low redshift clusters have been studied for over half a century now, the discovery of high redshift galaxy clusters (Gioia & Luppino 1994; Gioia 1998) has opened a new avenue for using them as tools to probe the evolution of large scale structure and galaxies from $z \sim 1$ to the present.

The existence of massive clusters at high redshift may constrain the mean matter density of the universe (Ω_M). In a high density universe ($\Omega_M \sim 1$), massive clusters would have formed fairly recently and their main epoch of growth would be from low redshift ($z \sim 0.3$) to the present (Carlberg et al. 1997). In this model, the existence of massive clusters at redshifts greater than 0.5 is highly unlikely and their number density evolves quickly with redshift (Gross et al. 1998; Carlberg et al. 1997). In a low density universe, however, structure formed early and quickly, “freezing out” at higher redshift and so the number density evolution is much milder. A flat, Λ -dominated ($\Omega_M + \Omega_\Lambda = 1$) universe predicts slightly stronger evolution than a open, low Ω_M model but the results are similar (Bahcall, Fan, & Cen 1997). The difference in the predicted number of massive clusters at $z \sim 0.8$ between low and high density models is several orders of magnitude; Bahcall & Fan (1998) and Donahue et al. (1998) quote a factor of $\sim 10^5$. As such, the existence of a few massive ($10^{14} M_\odot$), high redshift galaxy clusters can rule out a high Ω_M universe (Gioia 1998; Bahcall & Fan 1998; Gross et al. 1998).

Presently, there are three favored methods to measure cluster masses: measuring the cluster velocity dispersion (pioneered by Zwicky 1933); mapping the X-ray emissivity of the intracluster gas (Cavaliere & Fusco-Femiano 1976; Cavaliere & Fusco-Femiano 1978); or using weak and/or strong-lensing to trace the cluster mass distribution (Bartelmann 1995; Miralda-Escudé & Babul 1995; Fort & Mellier 1994). Each method, however, has uncertainties resulting from different sources which may over- or underestimate the mass significantly. For example, lensing traces the total matter distribution in a cluster but a cluster’s weak-lensing map is affected by any additional mass along the line of sight from the observer to the galaxies serving as the background sources, and the redshift distribution of the background sources is a considerable source of error. Lensing is also affected by the flat-sheet dilemma (Bartelmann 1995) which causes one to underestimate the true mass. As for using the velocity dispersion or X-ray emissivity, these are easily affected by cluster substructure; accretion of sub-groups can increase the former (Crone & Geller 1995), and deviation of the intracluster gas from hydrostatic equilibrium can introduce errors up to 50% in the mass estimate (Roettiger, Burns, & Loken 1996). To overcome the uncertainties inherent in

each method, it is best to use a combination of all three to study a cluster’s dynamics (Markevitch 1998; Smail 1997).

In this paper, we weigh the high redshift galaxy cluster MS1054–03 by measuring its velocity dispersion. This work complements the weak-lensing study completed by Luppino & Kaiser (1997; hereafter LK97) and the X-ray study by Donahue et al. (1998; hereafter D98) of this cluster. Our results are based on spectra collected with the Keck II Telescope of 24 cluster members. With this sample, we measure MS1054–03’s velocity dispersion (σ), estimate the corresponding dynamical mass, and compare our results to X-ray (D98) and weak-lensing (LK97) results. In addition, it has been observed that there is no evolution in the $\sigma - T_X$ relation for a sample of lower redshift clusters ($z \leq 0.54$; Mushotsky & Scharf 1997; hereafter MS97); we place MS1054–03 on the $\sigma - T_X$ plane to test this result at high redshift.

In our calculations, we use $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$, and $\Lambda = 0$ except where noted.

2. Data

Our objects were chosen from two target lists. Higher priority objects were cluster member candidates selected based on their I fluxes ($I < 22.1$) and two colors, $(R - I)$ and $(B - R)$. Lower priority objects were faint field and additional cluster member candidates selected based on their I magnitude alone ($22 < I < 24$). Our main criterion was to identify cluster members bright enough to measure absorption line velocity dispersions using the G-band (van Dokkum et al. 1998); the fainter galaxies were assigned lower priority on the slit-masks. The B and R images were kindly made available by G. Luppino and are described in LK97; the I image was taken with Keck/LRIS. The package FOCAS (*Faint Object Classification and Analysis System*; Valdes 1982) was used to measure the fluxes (total light within $r \sim 1.''2$). The target selection did not include galaxy morphology.

The spectra were taken with the Keck II Telescope in February 1997 during a two night run. Four multi-slit masks were used to cover a $6' \times 7.8'$ field; at MS1054–03’s redshift, this field corresponds to a region approximately $1.5 \times 1.9h^{-1} \text{ Mpc}$. Using the *Low Resolution Imaging Spectrograph* (LRIS; Oke et al. 1995) with the 831 mm^{-1} grating centered at 8200 \AA (instrumental resolution $\sigma_{instr} \sim 50 \text{ km/s}$), we integrated for two hours each on three of the masks and 2.6 hours on the fourth. Of the original 110 targets on the masks, useful spectra were obtained for 52 objects; the lost spectra were due to low signal to noise, scattered light, or a combination of both. A bright blue star also was included on all four masks to correct for the H_2O atmospheric absorption feature (7600 \AA). The seeing was $\sim 1''$ on both nights.

A combination of IRAF packages and customized programs were used to reduce the multi-slit spectra. The spectra were cleaned of cosmic rays using software made available by A. Phillips; the spectra were then flat-fielded, rectified, and wavelength calibrated using the software package

Extractor (Kelson 1998). The sky subtraction and the extraction of the spectra were done in the usual way using IRAF. The extracted spectra cover a wavelength range of $\sim 6800 - 9400 \text{ \AA}$ with a dispersion of $\sim 1 \text{ \AA/pixel}$.

To determine redshifts, we used the IRAF task XCSAO (Kurtz et al. 1992) to cross-correlate the 52 spectra with four galaxy templates: NGC7331 (morphological type SA(s)b), NGC4889 (E4), NGC2276 (SAB(rs)c), and an E+A galaxy. The E+A spectrum was created by adding an A star spectrum to NGC4889. In our wavelength range, the main features in a cluster galaxy spectrum are H δ , CaI (4227 \AA), G-band, H γ , Fe (4383.6 \AA), and H β ; in some members, the H and K break also is visible. We found that NGC7331 and the E+A galaxy were the best templates to use in confirming cluster members. The 24 galaxies confirmed to be cluster members are listed in Table 1, along with their heliocentric redshifts and positions.

In the same table, we include the eight additional cluster members from the D98 study. D98 actually has spectra for 12 cluster members but four overlap with our sample; we use our redshifts for these four since our errors are smaller. Comparison of the four overlapping redshifts shows that ours are slightly higher ($\overline{\delta z} \approx 0.0024 \pm 0.0044$). Although these differences are within 1σ of the estimated errors, we choose not to include D98’s redshifts in our final analysis since the offset in the four common members may indicate a slight bias between the two data sets.

The redshift errors for the galaxies in our set are small. Since we intended to measure dispersions of individual cluster members (van Dokkum et al. 1998), the spectra have unusually high signal-to-noise for a redshift survey which results in small errors. A combination of the grating’s high spectral resolution ($\sigma_{instr} \sim 50\text{km/s}$), the large number of sky lines used in the wavelength calibration, and the multiple absorption features used in the cross-correlation routine also reduced the errors. The dominant factor in the redshift error is the instrumental resolution of LRIS.

3. Results

In Fig. 1, we present an I image of the field with the 32 confirmed cluster members marked (including the eight from D98); galaxy 1484 is the Brightest Cluster Galaxy (BCG). The image is approximately 5.1 on a side ($1.3h^{-1} \text{ Mpc}$ at $z = 0.83$). MS1054–03’s striking structure is seen as the filament stretching from east to west; there also appears to be structure north and south of the cluster core.

The velocity distribution for the field and cluster galaxies is plotted in the upper panel of Fig. 2. Note how MS1054–03 stands out as a strong peak at $z = 0.83$. The lower panel of Fig. 2 contains a histogram of the 24 cluster members (noted by the solid boxes). The bin size (200 km/s) corresponds to three times the average error in the individual galaxy redshifts. In the same panel, D98’s 12 galaxies (dotted boxes) are also included and the bin size adjusted to their errors.

To determine the mean redshift and velocity dispersion of MS1054–03, we use the biweight, bootstrap, and jackknife methods of Beers, Flynn, & Gebhardt (1990) since they have proven to be robust estimators when dealing with small samples ($N < 50$). The biweight estimator is used to measure both the cluster’s redshift and its velocity dispersion. The corresponding errors are estimated using the bootstrap (redshift) and jackknife (velocity dispersion) algorithms. All of these methods take into account the associated error in the measurements. None of these methods assume that the cluster member velocity distribution is Gaussian.

Using the 24 confirmed members from our sample, we measure the cluster redshift to be $z = 0.8329 \pm 0.0017$, and the velocity dispersion to be $\sigma = 1170 \pm 150$ km/s; the latter is corrected to the cluster rest-frame by dividing by the factor $(1 + z)$ (Peebles 1993). If we include D98’s eight members in our weighted analysis and correct them for the systematic offset of $\overline{\delta z} \approx 0.0024 \pm 0.0044$, the cluster’s redshift decreases slightly (0.8323 ± 0.0017) and the velocity dispersion increases to 1230 ± 140 km/s. Due to the offset between our sample and D98’s, however, we use only our 24 members in the following analysis. Like Carlberg et al. (1996), we find that with more cluster members (24), the velocity dispersion decreases from the previous estimate which used only 12 members ($\sigma_{D98} = 1360 \pm 450$).

To estimate the mass using the velocity dispersion, we follow Ramella, Geller, & Huchra (1989) (also Nolthenius & White 1987) by first determining the cluster’s virial radius:

$$R_V = \frac{\pi \bar{z}}{H_0} \left\{ \frac{1}{2} \left[\frac{N_{mem}(N_{mem} - 1)}{2} \left(\sum_i \sum_{j>i} \theta_{ij}^{-1} \right)^{-1} \right] \right\} \quad (1)$$

where \bar{z} is the redshift of the cluster, N_{mem} is the number of cluster members, and θ_{ij} is the angular separation of cluster members i and j . The cluster’s virial mass follows as

$$M = \frac{6\sigma_{1D}^2 R_V}{G} \quad (2)$$

where M is the mass, σ_{1D} is the line-of-sight velocity dispersion ($\sigma = 1170 \pm 150$ km/s), and R_V is the virial radius. We determine R_V to be $1h^{-1}$ Mpc, and the corresponding mass to be $M = 1.9 \times 10^{15} h^{-1} M_\odot$. Using the error in the velocity dispersion, the corresponding error in our mass estimate is approximately $0.5 \times 10^{15} h^{-1} M_\odot$ ($\sim 25\%$).

We note that our simple method of estimating the mass does not take into account systematic errors which easily can change the mass estimate by a factor of two (Crone & Geller 1995; Cen 1996). Like many clusters, MS1054–03 is elongated along the plane of the sky (de Theije, Katgert, & van Kampen 1995; Binggeli 1982) with the main structure extending from east to west (see Fig. 1). The same elongation is seen in the X-ray and weak-lensing maps, so MS1054–03 may not be virialized or it may be triaxial, or it may be both. A dynamical treatment such as this is sensitive to non-virialization, deviation from an isothermal profile, substructure, and triaxiality; X-ray and lensing estimates also are sensitive to these factors but to different degrees. Thus, the formal errors quoted by the three methods used to estimate MS1054–03’s mass may be overshadowed by the errors introduced by these effects.

4. Discussion

4.1. Comparison to X-ray and Weak-Lensing Results

D98 have measured MS1054–03’s X-ray temperature with ASCA and mapped the luminosity of the cluster’s intracluster medium with the ROSAT HRI. By adopting an isothermal model in a matter-dominated universe ($\Omega_M = 1$), they use the X-ray temperature ($12.3 \pm_{2.2}^{3.1}$ keV) to estimate the cluster’s virial mass; the virial mass is chosen to correspond to a volume where the mean density is 200 times the critical density. Within this characteristic radius ($r_{200} = 1.5h^{-1}$ Mpc), the estimated mass is $0.74 \times 10^{15}h^{-1}M_\odot$. The difference in the X-ray and dynamical mass estimates may be due to difficulties in determining the correct shape, characteristic radius, and mass distribution of any cluster. For example, projection effects and nonequilibrium of the intracluster gas with the potential can result in an underestimate of the X-ray temperature and introduce errors up to 50% in the mass (Roettiger, Burns, & Loken 1996). D98 also note that measuring the virial masses of clusters becomes more difficult than measuring their X-ray temperatures with increasing redshift since virial masses depend on the adopted cosmology. While the two mass estimates differ, however, they do agree within their large uncertainties and both do support the main result which is that MS1054–03 is a massive cluster.

For the weak-lensing analysis, LK97 use ground-based images of MS1054–03 to estimate its mass distribution ($H_0 = 100h$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_M = 1$) out to a radius of $1h^{-1}$ Mpc. In their models, the cluster’s total enclosed mass depends on the redshift of the background sources (z_s); since this is unknown, they consider models where the background galaxies lie in sheets at $z_s = 1, 1.5, \& 3$. Depending on whether z_s is 3 or 1, the mass within a radius of $1h^{-1}$ Mpc can differ by more than a factor of five, $1 \times 10^{15}h^{-1}M_\odot$ to $5 \times 10^{15}h^{-1}M_\odot$ respectively. We find our mass estimate ($1.9 \pm 0.5 \times 10^{15}h^{-1}M_\odot$) best agrees with a weak-lensing model where the sources are at $z_s \sim 3$ if $\Omega_M = 1$. In a low density or Λ -dominated universe, however, the redshifts of the background sources for a given weak-lensing mass estimate will decrease for a given mass, e.g. from $z_s \sim 3$ to $z_s \sim 2$ for $M = 1 \times 10^{15}h^{-1}M_\odot$ ($R < 1h^{-1}$ Mpc).

The consistency between the three mass estimates for MS1054–03 confirms the existence of at least one massive galaxy cluster at high redshift ($z > 0.5$). With its high velocity dispersion and mass, MS1054–03 presents a substantial argument against a flat, matter-dominated ($\Omega_M = 1$) universe (D98; Gross et al. 1998; Bahcall 1998; Gioia 1998). In an $\Omega_M = 1$ universe, the number density of clusters evolves strongly from a redshift of 1 to the present whereas in an open ($\Omega_M \sim 0.3$) or Λ -dominated model, structure forms at higher redshift and the bulk of clusters are in place by $z \sim 1$ (Bartelmann, Ehlers, & Schneider 1993). At $z \sim 0.8$, the difference in the predicted number of clusters between $\Omega_M = 1$ and open (or Λ -dominated) models is several orders of magnitudes (Bahcall & Fan 1998 and D98 quote a factor of $\sim 10^5$), so the likelihood of finding a high redshift cluster is much greater in an open (or Λ -dominated) universe. Thus, the existence of a handful of clusters like MS1054–03 may be enough to rule out an $\Omega_M = 1$ universe (Gross et al. 1998; Carlberg 1997).

4.2. $\sigma - T_X$ Relation

In Fig. 3, we follow earlier work by MS97 at lower redshift by comparing MS1054–03’s velocity dispersion and X-ray temperature to values measured for other clusters ($0.19 < z < 0.55$). In Table 2, we list the clusters, their velocity dispersions, X-ray temperatures, and references. These particular clusters were selected from the literature based on their redshifts and that their X-ray temperatures were measured using the ASCA satellite. In Fig. 3, we fit a curve to the data using weighted least squares. The form of the fit is $T_X = a\sigma^n$ where both the constant a and the power n are variables; the fit is weighted by the errors in both σ and T_X . As previous workers have done (Edge & Stewart 1991; MS97; D98), we include a curve denoting the virial relation $kT_X\beta = \mu m_p\sigma^2$ with $\mu = 0.6$ and $\beta = 1.0$.

Despite being the hottest ($T_X = 12.3 \pm_{2.2}^{3.1}$ keV) and most distant cluster in the sample, MS1054–03 lies on the same trend as the lower redshift clusters, a result which suggests little or no evolution in the $\sigma - T_X$ relation. Also interesting is that the $\sigma - T_X$ relation for these clusters, including MS1054–03, follow the virialized model fairly well, indicating that both the X-ray gas and galaxies trace the same gravitational potential well. This has been noted by MS97 for a sample of lower redshift clusters ($0.14 < z < 0.55$). Our current work, which includes significantly more clusters than D98 in the redshift range $0.19 < z < 0.83$, confirms MS97’s conclusions to $z \sim 0.8$. Since MS1054–03 does not appear to be substantially less evolved than its lower redshift counterparts, it further suggests a low Ω_M or Λ -dominated universe since in these models cluster structure does not evolve significantly from $z \sim 0.8$ to now (Bartelmann et al. 1998; Bartelmann, Ehlers, & Schneider 1993).

An argument against MS1054–03 being as evolved as low redshift clusters is its elongation along the plane of the sky. It should be noted, however, that such structure is seen in some low and intermediate redshift clusters (White et al. 1993; Bird, Davis, & Beers 1995; Markevitch et al. 1998) and may indicate triaxiality rather than non-virialization. A further investigation of triaxiality and substructure is not possible with the present set of 32 members. MS1054–03’s agreement with trends relating X-ray temperatures and velocity dispersions derived from low and intermediate redshift clusters (Fig. 3; D98; MS97) suggests that despite its asphericity and substructure, MS1054–03 may be just as evolved as these clusters.

5. Conclusions

We present a dynamical study of the high redshift galaxy cluster MS1054–03 using 24 confirmed cluster members ($6' \times 7.8$ field) to improve D98’s estimate of the cluster redshift and velocity dispersion. With the 24 members, we find that MS1054–03 has a mean $z = 0.8329 \pm 0.0017$ and a velocity dispersion of 1170 ± 150 km/s. Its corresponding dynamical mass within $1h^{-1}$ Mpc is $1.9 \pm 0.5 \times 10^{15} h^{-1} M_\odot$.

We find that the dynamical and X-ray mass estimates agree within the errors, leading us to conclude that the intra-cluster gas and galaxies may be in equilibrium with the cluster’s potential (at least to a radius of $1h^{-1}$ Mpc). In addition, comparison of these two mass estimates with the weak-lensing results places a constraint on the redshifts of the background sources lensed by MS1054–03; the best agreement is for $z_s \sim 3$ ($q_0 = 0.5$). For this weak-lensing mass ($1 \times 10^{15} h^{-1} M_\odot$), Luppino & Kaiser (1997) estimate the corresponding cluster M/L_V to be $350h (M/L_V)_\odot$.

With this velocity dispersion and an X-ray temperature of $12.3 \pm_{2.2}^{3.1}$ keV (D98), MS1054–03 lies on the same trend in the $\sigma - T_X$ relation as a sample of lower redshift clusters ($0.19 < z < 0.55$). This consistency between MS1054–03 and the lower redshift sample supports no evolution in the $\sigma - T_X$ relation to $z \sim 0.8$. In addition, the agreement of these clusters with the virial relation $kT_X\beta = \mu m_p \sigma^2$ (with $\beta = 1.0$ and $\mu = 0.6$) is consistent with both the X-ray gas and galaxies tracing the same gravitational well even at high redshift.

Despite MS1054–03’s high redshift and aspherical morphology, the consistency between our results with X-ray and weak-lensing studies argues for a well-developed cluster core similar to those at lower redshift. Certainly, there is little disputing MS1054–03’s mass, a result which is difficult to accommodate in a high Ω_M universe. The lack of evolution in the $\sigma - T_X$ relation to a redshift of $z \sim 0.8$ also argues for early structure formation and thus a low density or Λ -dominated model. Although these results do not effectively rule out a high density universe, they do add to the mounting support for a low density (or Λ -dominated) one.

In the future, we plan to continue our dynamical study of MS1054–03 by adding more cluster members to our present set; the larger set will allow us to probe the cluster’s substructure and refine our naive approach of assuming spherical symmetry and hydrostatic equilibrium to measure the mass. We will combine the spectra with an HST WFPC2 mosaic of the cluster (van Dokkum, in preparation) taken in May 1998. With the spectra and high resolution images, we will probe MS1054–03’s optical substructure, examine the individual galaxy profiles of cluster members, and better compare MS1054–03 to galaxy clusters at lower redshift.

We would like to acknowledge G. Luppino, I. Gioia, and M. Donahue for the generous use of their data. We thank A. Zabludoff for her insightful thoughts on this paper, and the anonymous referee for his comments. We also appreciate the efforts of those at the Keck telescope who developed and supported the facility and instruments that made this program possible. Support from STScI grants GO-05991.01-94A, AR-05789.01-94A, and GO-07372.01-96A is gratefully acknowledged.

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Table 1. Redshifts of Cluster Members

Galaxy #	z	Offset E/W ^a (+/- arcsec)	Offset N/S ^a (+/- arcsec)
0696	0.8312 ± 0.0002	58	-84
0997	0.8390 ± 0.0002	-136	-58
1163	0.8329 ± 0.0002	63	-29
1209	0.8380 ± 0.0002	-84	-24
1280	0.8371 ± 0.0002	-122	-17
1294 (D5)	0.8353 ± 0.0002	-22	-13
1325	0.8317 ± 0.0002	-53	-10
1329 (D2)	0.8346 ± 0.0002	24	-6
1340	0.8403 ± 0.0002	-45	-2
1359 (D10)	0.8175 ± 0.0002	-39	0
1405	0.8367 ± 0.0002	46	-4
1430	0.8239 ± 0.0002	26	7
1457	0.8420 ± 0.0002	17	0
1459	0.8454 ± 0.0002	-6	8
1484 (BCG; D1)	0.8314 ± 0.0002	0	0
1567	0.8282 ± 0.0002	71	25
1583	0.8259 ± 0.0002	52	23
1655	0.8397 ± 0.0002	38	34
1656	0.8224 ± 0.0002	38	31
1701	0.8314 ± 0.0002	44	48
1760	0.8249 ± 0.0002	34	56
1834	0.8392 ± 0.0002	58	73
1942	0.8308 ± 0.0002	59	98
1986	0.8250 ± 0.0002	134	111
D3	0.8127 ± 0.0003	31	-19
D4	0.8213 ± 0.0007	21	21
D6	0.8209 ± 0.0010	-29	-14
D7	0.8286 ± 0.0010	-32	-12
D8	0.8353 ± 0.0006	-38	-8
D9	0.8332 ± 0.0010	-44	-6
D11	0.8378 ± 0.0030	-82	-45
D12	0.8319 ± 0.0020	-99	-39

^aThe offset is given from the central BCG; its coordinates as measured from an HST image (D98) are $(\alpha, \delta)_{2000} = (10^h 56^m 59.9^s, -3^\circ 37' 37.3'')$.

Note. — The last eight galaxies in this table are from D98.

Table 2. Cluster Sample: Velocity Dispersions and X-Ray Temperatures

Galaxy Cluster	z	σ	Reference (σ)	T_X	Reference (T_X)
A2390	0.2279	1093 ± 61	1	8.9 ± 0.9	2
MS0440	0.1965	606 ± 62	1	5.3 ± 1.3	2
MS0451+2 (A520)	0.2010	988 ± 76	1	8.6 ± 0.9	2
MS0839	0.1928	749 ± 104	1	3.8 ± 0.4	3
MS1008	0.3062	1054 ± 107	1	7.9 ± 1.2	4
MS1224	0.3255	802 ± 90	1	4.3 ± 0.7	4
MS1358	0.3290	937 ± 54	1	6.6 ± 0.5	4
MS1455	0.2570	1133 ± 140	1	5.2 ± 2.2	5
MS1512	0.3726	690 ± 96	1	3.8 ± 0.4	4
MS0016	0.5466	1234 ± 128	1	7.6 ± 0.7	6
MS0451-3	0.5392	1371 ± 105	1	10.4 ± 1.2	7
MS1054	0.8329	1170 ± 160	This Paper	12.3 ± 3.1	8

References. — (1) Carlberg et al. 1996; (2) Mushotzky & Scharf 1997; (3) Tsuru et al. 1996; (4) Henry 1997; (5) Allen et al. 1996; (6) Hughes & Birkinshaw 1995; (7) Donahue 1996; (8) D98

FIGURE CAPTIONS

Fig. 1.— A 900 second exposure I image of the field taken with the Keck I telescope; the field is approximately $5.1'$ on a side ($1.3h^{-1}$ Mpc at $z = 0.83$). The 24 confirmed cluster members are shown; the numbers correspond to our galaxy catalog. Galaxy 1484 is the brightest cluster galaxy (BCG). We also identify the eight cluster members from D98 which did not overlap with our set (see Table 1).

Fig. 2.— *Upper Panel:* Histogram (bin size 1000 km/s) of the 60 galaxies for which we have redshifts. MS1054–03 corresponds to the strong peak at $z = 0.83$. *Lower Panel:* Distribution of the 24 cluster members in velocity space (bin size 200 km/s). The solid line corresponds to our data set while the dotted refers to the 12 cluster members from D98 (four galaxies overlap between D98’s and our data sets).

Fig. 3.— Comparison of the velocity dispersion of MS1054–03 ($\sigma = 1170 \pm 150$ km/s) and X-ray temperature ($12.3 \pm_{2.2}^{3.1}$ keV; D98) to that of 11 clusters at intermediate redshift ($0.19 < z < 0.55$); MS1054–03 is the filled circle. We fit a curve to the data using a weighted least squares (solid line) and include the fit’s 1σ rms (dotted lines). The fit is of the form $T_X = a\sigma^n$ where both the constant a and the power n are variables; the fit is weighted by errors in both σ and T_X . Note that the axes are linear. Also included is a dashed line denoting the virial relation $kT_X\beta = \mu m_p\sigma^2$ where $\mu = 0.6$ and $\beta = 1$. The least squares fit of $T_X = a\sigma^n$ seems to agree well with a virialized model for clusters in this redshift range.

This figure "MS1054_fig1.jpg" is available in "jpg" format from:

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