Dissecting the Strong-lensing Galaxy Cluster MS 0440.5+0204. II. New Optical Spectroscopic Observations in a Wider Area and Cluster Dynamical State

Eleazar R. Carrasco1, Tomás Verdugo2, Verónica Motta3, Gael Foëx3, E. Ellingson4, Percy L. Gomez5, Emilio Falco6, and Marceau Limousin7

1 Gemini Observatory/NSF’s NOIRLab, Casilla 603, La Serena, Chile; rodrigo.carrasco@noirlab.edu
2 Observatorio Astronómico Nacional, Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, B.C., Mexico
3 Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Avda. Gran Bretaña 1111, Valparaíso, Chile
4 Center for Astrophysics and Space Astronomy, 389 UCB, University of Colorado, Boulder, CO 80309-0389, USA
5 W. M. Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI 96743, USA
6 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
7 Aix Marseille Univ, CNRS, CNES, LAM, F-13013 Marseille, France

Received 2020 August 17; revised 2021 May 28; accepted 2021 June 14; published 2021 September 8

Abstract

We present an optical study of the strong-lensing galaxy cluster MS 0440.5+0204 at $z = 0.19593$, based on CFHT/MegaCam $g'$, $r'$ photometry and GMOS/Gemini and CFHT/MOS/SIS spectroscopy in a broader area than previous works. We have determined new spectroscopic redshifts for the most prominent gravitational arcs surrounding the central galaxy in the cluster. The new redshifts and the information provided by the photometric catalog allow us to perform a detailed weak- and strong-lensing mass reconstruction of the cluster. The large number of member galaxies and the area covered by our observations allow us to estimate more accurately the velocity dispersion and mass of the cluster and to examine in detail the nature of the cluster and surrounding structures. The dynamical mass is in good agreement with the mass inferred from the lensing analysis and X-ray estimates. About 68% of the galaxies are located in the inner $\lesssim 0.86 h_{70}^{-1}$ Mpc region of the cluster. The galaxy redshift distribution in the inner region of the cluster shows a complex structure with at least three substructures along the line of sight. Other substructures are also identified in the galaxy density map and in the weak-lensing mass map. The member galaxies in the northeast overdensity are distributed in a filament between the clusters MS 0440.5+0204 and ZwCL 0441.1+0211, suggesting that these two structures might be connected. MS 0440.5+0204 appears to be dynamically active, with a cluster core that is likely experiencing a merging process, and with other nearby groups at projected distances of $\lesssim 1 h_{70}^{-1}$ Mpc that could be being accreted by the cluster.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Redshift surveys (1378); Gravitational lensing (670)

Supporting material: machine-readable table

1. Introduction

Galaxy clusters are the largest gravitationally bound systems in the universe. They serve as unique laboratories in which to study the formation of large-scale structure and galaxy evolution. Clusters are excellent locations in which to probe the mass distribution of both baryons and dark matter (DM), using a variety of multiwavelength data (UV/optical, near-infrared, X-ray) and over a wide range of scales. Moreover, in the UV and optical wavelength regimes, gravitational lensing has become an important tool for measuring the mass distribution at different scales without any assumption of the dynamical state and the nature of the intervening matter. In the last decade, improved lensing models (e.g., Limousin et al. 2007; Newman et al. 2013; Zitrin et al. 2013; Diego et al. 2015; Jauzac et al. 2015) have allowed us to better understand the mass profile on scales from $\sim 10 h_{70}^{-1}$ kpc (strong-lensing (SL) regime) down to $\sim 5 h_{70}^{-1}$ Mpc (weak-lensing (WL) regime). Indeed, it has been evident that it is necessary to combine complementary probes of the gravitational potential in order to recover the mass density profiles in a better way (e.g., Verdugo et al. 2011, 2016; Limousin et al. 2013; Newman et al. 2013; Monna et al. 2015), in particular to constrain the mass in the external regions of the clusters, since strong lensing is accurate only in the inner regions (see Verdugo et al. 2016, for a discussion).

An interesting new approach to measure the mass profile in galaxy clusters at scales between SL and WL regimes is to look at “regular” galaxy clusters, i.e., clusters where no obvious substructures are detected, and for which a single DM halo modeling can be applied. Verdugo et al. (2011, 2016) show that it is possible to obtain a complete understanding of the mass profile at these scales by combining SL modeling with dynamical measurements. Although this method constrains large-scale properties inaccessible to SL models, it requires observational constraints and assumptions about the dynamical state of the system. This approach requires detailed spectroscopic analysis of the clusters based on the measurement of the redshift for a large number of galaxies in the cluster and its environment. From the observational point of view, this could be challenging, because it requires access to a large amount of telescope time. With the advent of new observational techniques that allow spectroscopic and photometric redshifts of hundred of galaxies to be obtained in large areas of the sky, systematic determination of galaxy redshifts in clusters began only recently (e.g., Rines et al. 2013; Geller et al. 2014; Balestra et al. 2016; Bonoli et al. 2020).

To extend the method presented in Verdugo et al. (2011, 2016), we test an analogous and improved study of the SL galaxy cluster MS 0440.5+0204 located at $z \sim 0.19$. MS 0440.5+0204 is a relatively massive galaxy cluster with high X-ray luminosity.
Gemini South. The locations of cluster member galaxies are depicted in the smoothed Chandra X-ray image of the central 60″ region of the cluster (0.2–6.0 keV energy). The top left inset shows the central 30″ × 30″ region of the cluster (~100 h^70\text{kpc} × ~100 h^70\text{kpc}) with the six distinct nuclei embedded in a common symmetric envelope. The bottom left inset shows the HST WFPC2 F702W image, with the local median average of the gravitational arc systems and subcomponents, including the radial arcs M4.2 and M5.2 within the central 60″ region of the cluster subtracted. Member galaxies are identified with numbers and letters (Section 2.4 and Table 3), along with the different gravitational arc systems and subcomponents, including the radial arcs M4.2 and M5.2 (see Table 2). North is up, and east is left.

Figure 1. Color g′, r′, i′ composite image of the central ~5′ × 5′ (1 × 1 h^70\text{kpc}^2 at z = 0.196) region of the MS 0440.5+0204 cluster observed with GMOS at Gemini South. The large number of member galaxies allows us to study the presence of substructures and to confirm (or reject) the relaxed nature of the cluster. The results allow us also to characterize the mass profile from the SL region of the cluster up to medium scales. A detailed explanation of the lensing modeling of MS 0440.5+0204, and the comparison with measured masses reported previously in the literature, are presented in Verdugo et al. (2020, hereafter Paper I).

(L_X \sim 6 \times 10^{44} \text{ erg s}^{-1}, \text{Hicks et al. 2006}). It was discovered in X-rays in the Extended Medium Sensitivity Survey by Gioia et al. (1990). This system is a good example of a so-called “regular” cluster, where no obvious substructures are present. This assumption is based on a previous X-ray and kinematic analysis of the cluster by Gioia et al. (1998, hereafter G98) based on only 40 confirmed members. In its center, the cluster is dominated by a multi-nucleus cD galaxy (hereafter the brightest cluster galaxy, or BCG, Luppino et al. 1993), with six distinct nuclei merging within a common symmetric envelope of ~48″ (~157 h^70\text{kpc}) diameter. The BCG in MS 0440.5+0204 is quite similar to the central galaxy in A3827, a supergiant elliptical that appears to be in the process of cannibalizing at least four other galaxies (Carrasco et al. 2010, and references therein). Surrounding the BCG are at least five gravitationally lensed arc systems and two radial arcs (Luppino et al. 1993; G98), corresponding to lensed sources located at different redshifts. The different gravitational arc systems and their subcomponents, within the central 1′ × 1′ region of the cluster, are shown in Figure 1 (bottom left inset). The mass profile of this cluster has been studied previously from the ground and space by combining weak lensing and X-ray analysis (G98; Hicks et al. 2006; Hoekstra et al. 2012, 2015; Mahdavi et al. 2013). Despite the extensive multiwavelength studies presented in the literature, the number of galaxies with confirmed redshift is small. The same is true for the lensed arcs. Only one gravitational arc system (S1) has its redshift confirmed via spectroscopic observations (see Figure 1). Therefore, no detailed SL analysis of this cluster exists except for an early attempt by G98, who used different lensing models to estimate the redshifts of the lensed sources based on Hubble Space Telescope (HST) images. To provide a reliable measurement of the mass profile at “medium” scales, it is imperative to determine, with good precision, the spectroscopic redshift of the lensed arc systems and the galaxies belonging to the cluster in a wider area.

This is the second paper of a pair, with the aim of putting forward detailed dynamical measurements of the galaxy cluster MS 0440.5+0204 based on analysis of new redshifts obtained for a large number of galaxies (~100) up to ~2 × r^200 on the sky. The large number of member galaxies allows us to study the presence of substructures and to confirm (or reject) the relaxed nature of the cluster. The results allow us also to characterize the mass profile from the SL region of the cluster up to medium scales. A detailed explanation of the lensing modeling of MS 0440.5+0204, and the comparison with measured masses reported previously in the literature, are presented in Verdugo et al. (2020, hereafter Paper I).
The paper is organized as follows. Section 2 provides details about the observations, the data reduction, and the redshift estimation of the lensed sources and the galaxies. In Section 3 we provide a brief explanation of the lensing models and highlight the main result obtained from the lensing analysis presented in Paper I. In Section 4 we present the dynamical analysis of the cluster and discuss our findings. Finally, in Section 5, we summarize our results and present our conclusions.

Throughout this work we adopt the following cosmological parameters: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \ h_{70} \ \text{km s}^{-1} \ \text{Mpc}^{-1}$. With this cosmology 1″ corresponds to 3.24 $h_{70}^2$ kpc at the redshift of the cluster ($z = 0.196$). All magnitudes presented in this paper are quoted in the AB system.

2. Observations

2.1. Gemini Data

The images and spectroscopic data were obtained with the Gemini Multi-Object Spectrograph (hereinafter GMOS; Hook et al. 2004) mounted at the Gemini South telescope in Chile, in queue mode.

The central 5′.5 × 5′.5 region of the galaxy cluster MS 0440.5 +0204 was observed with the $g'$ (3 × 300 s exposures), $r'$ (3 × 200 s exposures), and $i'$ filters (3 × 200 s exposures) on 2011 November 12 UT (program ID: GS−2011B−Q−59), during dark time, in photometric conditions, and with median seeing values of 0″.51, 0″.50, and 0″.57 in $g'$, $r'$, and $i'$ filters, respectively. All images were processed with the reduction package THELI (Erben et al. 2005; Schirmer 2013). The science frames were bias/overscan-subtracted, trimmed, and flat-fielded. The resulting processed images were registered to common pixel and sky coordinate positions using the program SCAMP (Bertin 2006) called from THELI. A common astrometric solution for the three filters was derived using an external catalog generated from archival Canada–France–Hawaii Telescope (CFHT) images observed with MegaCam (see Section 2.2 for details). The astrometric calibrated images were sky-subtracted using constant values, resampled to a common position, and then stacked by filter using the program SWARP (Bertin 2010) called from THELI. The final coadded images were normalized to 1 s exposure. Although the GMOS images were obtained under photometric conditions, no photometric standard stars were observed during the night. Thus, to calibrate the photometry, we used the average magnitude zero-points listed on the GMOS public web page\footnote{http://www.gemini.edu/node/10445} of 28.15, 28.23, and 27.93 mag for the $g'$, $r'$, and $i'$ filters, respectively.

We used program Source Extractor version 2.19.5 (Bertin & Arnouts 1996) and the GMOS image in the $r'$ filter for object detection and photometry (our primary filter). The photometric parameters in the $g'$ and $i'$ filters were extracted for those objects detected in the $r'$ image. The MAG\_AUTO parameter was adopted as the value for the total magnitude of the objects. Colors were derived by measuring fluxes inside a fixed circular aperture of 1″ diameter. The star–galaxy separation was done using the CLASS\_STAR and FLUX\_RADIUS parameters. All objects with CLASS\_STAR < 0.3 and FLUX\_RADIUS > 2.5 pixels were selected and flagged as galaxies. The number counts for the objects classified as galaxies reach their maximum at $g' \sim 24.8$ mag and at $r' \sim 24.3$. The galaxy classification was checked visually and by plotting pairs of parameters (see Carrasco et al. 2006, and references therein). In both cases the classifications are consistent for ≳95% of the objects classified as galaxies down to $r' \sim 24.3$ mag. Using the number count information given above and the uncertainties in the galaxy classification, we have adopted the value of $r' = 24$ mag as our limiting magnitude.

The final GMOS photometric catalog contains total magnitudes, colors, and structural parameters for 355 objects classified as galaxies brighter than $r' = 24$ ($M_r = −15.91$ at the distance of the cluster, using a distance modulus of 39.91). The color composite ($g', r', i'$) image of the central 5′ × 5′ region of the cluster covered by GMOS is shown in Figure 1. The top left inset in the figure shows the BCG with the six distinct nuclei embedded in a common symmetric envelope. The X-ray contours in the figure are from the Chandra smoothed images. The arcs and arclets belonging to the gravitational arc systems M1, M2, M3, M4, M5, and S1 are shown in the bottom left inset of Figure 1.

The GMOS photometric catalog is mainly used to select the galaxies for spectroscopic follow-up. The galaxies were selected by their $r'$ magnitudes and ($g' - r'$) colors. Galaxies brighter than $r' = 22.5$ mag and inside the area delimited by the two dashed lines in Figure 2 (red triangles) were selected as potential targets for spectroscopy. Ninety-eight out of 134 galaxies (∼73% of the sample) were included in four GMOS masks. It is worth noting that, despite the remarkable nature of the gravitational arc system in MS 0440.5+0204, no accurate photometric nor spectroscopic redshifts for the lensed sources exist. Only the distorted arclike galaxy S1 has a secure spectroscopic redshift obtained by G98. To model the arc system in detail and hence constrain the mass of the cluster, the redshifts of the lensed sources have to be determined. To secure the redshifts, the brightest lensed sourced presented in the gravitational systems M1, M2, M3, M4, M5, and the source S1 (lower left inset in Figure 1) were included in two of the designed masks.

The GMOS multiobject observations were carried out a year later, between 2013 January 13 and February 4 UT (Program ID: GS-2012B-Q-53), during dark time and under photometric conditions. All spectra were acquired using the R400+ grating, 1″ slits, and 2 × 2 binning. The two masks, with 15 strongly lensed features and some of the faintest galaxies in the cluster, were observed with the nod-and-shuffling technique in band
shuffling mode (Glazebrook & Bland-Hawthorn 2001), using the OG515 blocking filter, and centered at 7500 Å. The two other masks were observed using a central wavelength of 6000 Å. Offsets of 70 and 50 Å toward the blue and the red were applied between exposures to avoid the loss of any emission and/or absorption lines that could, by chance, lie in the gaps between CCDs. The spectroscopic observation log is summarized in Table 1. For each mask, spectroscopic flats and spectra of CuAr comparison lamps were taken before or after each science exposure. To calibrate the science spectra in flux, the spectrophotometric standard stars LT T239 and LT T3864 were observed with the same instrument setup. However, the spectra were obtained on a different night (2012 August 29 UT) and under different observing conditions, providing only a relative flux calibration of the science spectra.

All spectra were reduced with the Gemini GMOS package version 1.14,7 following the standard procedures for multi-object spectrograph (MOS) and nod-and-shuffle MOS observations. The science exposures, spectroscopic flats, and CuAr comparison lamps were overscan- and bias-subtracted and trimmed. Spectroscopic flats were processed by removing the calibration unit and GMOS spectral response and normalized, leaving only the pixel-to-pixel variations. The two-dimensional science spectra were then flat-fielded, wavelength-calibrated, rectified (S-shape distortion corrected), and extracted to one-dimensional format. The obtained rms for the wavelength solution varied between ∼0.10 and 0.20 Å. For the 1″ slits, the final spectra have a resolution of ∼7.1 Å (measured from the FWHM of the sky lines), a dispersion of ∼1.37 Å pixel−1, and an average wavelength coverage of ∼4000–9500 Å (the coverage depends on the slit position in the GMOS field of view).

2.2. CFHT Data

The MS 0440.5+0204 cluster was observed with MegaCam at CFHT as part of the Canadian Cluster Comparison Project (CCCP—Hoekstra et al. 2012; Mahdavi et al. 2013), using the g′ and r′ filters, under photometric conditions. The images were reprocessed using the Elixir pipeline.10 The photometric calibration of the individual images was obtained using photometric standard stars obtained during the night of observation. The calibrated images were then coadded into a single image per filter using the MegaPipe image stacking pipeline11 (Gwyn 2008) at the Canadian Astronomy Data Center (CADC). The final MegaCam coadded images have a sky level of 0 ADU and are scaled to have a photometric zero-point of 30 mag in the AB system. The final coadded images have effective exposure times of 2440 and 6060 s with average seeing of 0.989 and 0.85 s in g′ and r′ filters, respectively.

The object detection and photometry were performed following the same recipe used with the GMOS images. In summary, the MegaCam r′-band image was used as the primary filter for object detection with Source Extractor (Bertin & Arnouts 1996). The photometric parameters in the g′ band were determined only for those objects detected in common with the r′-band image (dual mode). The parameter MAG_AUTO was adopted as the value for the total magnitude of the objects. The colors of the objects were estimated by measuring the flux inside a fixed circular aperture of 1″ diameter. Objects with CLASS_STAR < 0.3 and FLUX_RADIUS > 2.8 pixels in the r′ filter were selected as galaxies. We checked the objects classified as galaxies by plotting pairs of parameters and by visual inspection, as we did for the GMOS images in Section 2.1. We found that ≥90% of the galaxies were classified identically by the three methods down to r′ ∼ 24.3 mag (g′ ∼ 24.8 mag). The galaxy counts calculated using the objects classified as galaxies reach their maximum at r′ > 24.5 (g′ > 25 mag). Using this information and the uncertainties in the galaxy classification above r′ ∼ 24.3 mag, we have adopted a conservative value of r′ = 24 mag for our limiting magnitude.

The final catalog contains the magnitudes, colors, and structural parameters of 5547 objects classified as galaxies brighter than ∼24 mag in the r′ filter (our completeness limit). It is worth clarifying that we use the photometric catalog constructed from the CFHT/Megacam archival images to analyze the projected distribution of the galaxies in the cluster beyond the area covered by GMOS (see Section 4) and to build the catalog used in the WL analysis presented in Paper I and summarized in Section 3.1.

2.3. Redshifts of the Lensed Sources

We attempted to determine the redshifts of the lensed sources in gravitational arc systems M1, M2, M3, M4, M5, and S1 (see bottom left inset in Figure 1) by searching for clear spectroscopic features in their spectra. The redshifts of the lensed sources S1, M1.1–M1.4, and M2.1–M2.2 were determined using the emission lines in the arc spectra. The optical spectra of those lensed with spectroscopically secure redshifts are shown in Figure 3. The redshifts were measured by employing a line-by-line Gaussian fitting with the program RVIDLINES implemented in the IRAF RV package. From the [O II] λ3727, Hβ λ4340, Hβ λ4863, and [O III] λ5007 emission lines presented in the spectrum of the S1 arclike source, we have obtained a redshift of 0.53223. The redshift is in good agreement with the value of 0.53230 obtained by G98, after the redshift is corrected by a zero-point offset (see Section 2.4). The spectra of the lensed sources M1.1, M1.2, M1.3, and M1.4 show a strong emission line located at ∼7834 Å, which may be related to [O II] λ3727 at z ∼ 1.1. Another possibility is that this is a strong Lyα λ1216 emission line at z ∼ 5.4. However, this high-redshift solution is unlikely, since the previous model (G98) and our own estimation locate the source at a redshift between 0.53 and 1.1. For the system M1 we obtained an average redshift of 1.10148. The spectra of the M2.1 and M2.2 arcs show several emission lines at 7284 Å, 9501 Å, 9686 Å, and 9785 Å, corresponding to [O II] λ3727, Hβ λ4863, and [O III] λ5007, respectively. From these lines, we obtained an average redshift for the M2 arc system of 0.9543.

---

7 https://www.gemini.edu/node/11823
10 http://www.cfht.hawaii.edu/Instruments/Elixir/
11 http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/megapipe/
No spectroscopic features were found in the spectra of the M4.1, M4.2, M4.3, M5.1, and M5.2 arcs. However, there is a weak emission line present in the spectra of the M3.1 and M3.2 arcs (no spectroscopic features are seen in the spectra of the M3.3 arc). The emission line, located at 7156 Å, may correspond to [O III] λ2321 at z ∼ 2.1. Assuming an emission from [O III] λ2321 and using a Gaussian fitting, we obtain an average redshift of z = 2.0834. The 1D and 2D summed spectrum of the M3.1 and M3.2 arcs is shown at the bottom of Figure 4. Our calculation of spectroscopic redshift is supported by phot-z estimated using the GMOS magnitudes in $g$, $r$, and $i$ and the ESO/SOFI magnitude in the $J$ band using the HYPERZ software (Bolzonella et al. 2000). The infrared data were obtained with the SofI camera on the New Technology Telescope at the European Southern Observatory (ESO), La Silla Observatory in Chile (Moorwood et al. 1998). The observation in the $J$ band was carried out on 1998 October 29 (PROG = 62.O-0143, ID = 4271), with a total exposure time of 180 s. The data were reduced using the Eclipse data analysis software package (Devillard 1997). From the fitting results, we estimate phot-z of 2.02 ± 0.08 and 1.95 ± 0.07 for the M3.1 and M3.2 arcs respectively. The resulting probability distribution functions (PDFs) from HYPERZ for the arcs are shown in Figure 4 (top panel). We are aware of the uncertainties introduced using only four photometric bands in the phot-z determination. However, if we include the magnitudes estimated by Luppino et al. (1993) in $B$, $V$, $R$, and $I$, our results do not change.

The redshifts of the gravitational arc systems with secure values are presented in Table 2. The residual of the average shift in redshift of all measurements provided by RVIDLINES was used to estimate the errors. The errors in the redshift determination varied between 0.00016 and 0.00044. The final redshifts used in the lensing model are listed in the last column of the table.

### 2.4. Redshifts of the Galaxy Sample

We determined the redshifts of the galaxies observed with GMOS using the programs implemented inside the IRAF RV package. The spectra were visually inspected to search for obvious absorption and/or emission features characteristic of early- and late-type populations. For non-early-type spectra, the routine RVIDLINES was used, employing a line-by-line Gaussian fit. The errors of the measurements were estimated using the residual of the average shift in redshift of all measurements provided by the program. For normal early-type spectra, the cross-correlation statistic value of Tonry & Davis (1979) implemented in the program FXCOR was used. The observed spectra were correlated with four templates with high signal-to-noise ratio (S/N). The errors of the redshifts were estimated based on the $R$ statistic value of Tonry & Davis (1979). We were able to measure the redshifts for 96 of the 98 galaxies targeted in the four masks (≈98% success rate) plus one additional galaxy, which was found by chance in one slit.

In order to increase the number of galaxies with confirmed spectroscopic redshifts to be used in the dynamical analysis, the 97 measured redshifts presented above were combined with the 57 spectroscopic redshifts reported by G98 and with the 113 unpublished spectroscopic redshifts obtained by Yee et al. (1996) as part of the CNOC cluster Redshift Survey (Carlberg et al. 1994). The spectroscopic observations were conducted at CFHT using the MOS/SIS multiobject spectrograph (hereafter CFHTMOS; Le Fèvre et al. 1994), covering an area of ∼0°.45 × 0°.14 (∼5.3 × 1.6 h_70^{-2} Mpc^2 in the cluster rest frame). We refer the reader to Yee et al. (1996) for details about the data reduction and the criteria used to select the candidate cluster members. The large number of spectroscopic redshifts
and the area covered by the CFHTMOS observations allow us to study more accurately the dynamical state of the cluster and the spatial distribution of the member galaxies, and to analyze whether there are other structures at large scale that could be potentially connected to MS 0440.5+0204 (see Section 4.4 for details).

The combined spectroscopic sample contains 267 measured redshifts for 204 galaxies. Fifty-one galaxies have more than one redshift estimation among the three data sets: 39 galaxies have two measurements and 12 have three. One of the galaxies has two redshift determinations in the CFHTMOS sample. The large number of galaxies with multiple redshift measurements observed in common allows us to obtain a more accurate redshift, obtain an assessment of the general quality of the data, identify discordant redshifts, and find potential zero-point shifts between data sets. If the difference in the measured redshifts for a given galaxy and the zero-points of different instruments were significant, we could have introduced serious systematic errors in the resulting velocity dispersion and in the dynamical analysis of the cluster.

To build a coherent catalog to be used in the dynamical analysis, we compare the galaxy redshifts observed in common between the three different samples. Figure 5 shows the residual of the velocities as a function of the internal quadratic errors for the galaxies observed in common with G98 (top panel) and CFHTMOS (lower panel). A zeroth-order polynomial fitting of the data with a 3σ clip (to remove outliers) gives mean residuals of \( \sim 180 \text{ km s}^{-1} \) (rms of 151 km s\(^{-1}\)) and \( \sim 151 \text{ km s}^{-1} \) (rms of 76 km s\(^{-1}\)) for the galaxies observed in common with G98 and CFHTMOS, respectively. The derived mean residual shifts are similar, which is expected since both G98 and CFHTMOS data sets were obtained using the same telescope and instrument. The results are also consistent with the mean shifts obtained when comparing the 14 galaxies observed in common between CFHTMOS and G98. The comparison gives a mean residual shift of \( \sim 15 \text{ km s}^{-1} \) (rms \( \sim 77 \text{ km s}^{-1} \)), which is negligible compared to the rms, and consistent with the fact that the two samples were obtained using the same observational capabilities.

Even though the derived mean residual shifts are similar, the comparison between GMOS and G98 shows a large dispersion

| System (1) | Arc (2) | R.A. (3) | Decl. (4) | \( z_{\text{spec}} \) (5) | \( z_{\text{G98}} \) (6) | \( z_{\text{final}} \) (7) |
|-----------|--------|---------|----------|----------------|----------------|----------------|
| 0         | S1     | 04 43 11.17 | +02 10 10.49 | 0.53223   | 0.53230\(^a\) | 0.53223   |
| I         | M1.1 (A8) | 04 43 10.44 | +02 10 34.54 | 1.10125   | 0.53230\(^a\) | 1.01048   |
|           | M1.2 (A9) | 04 43 10.74 | +02 10 29.85 | 1.10139   | 0.53230\(^a\) | 1.01048   |
|           | M1.3 (A12) | 04 43 10.66 | +02 10 06.56 | 1.10176   | 0.53230\(^a\) | 1.01048   |
|           | M1.4 (A24) | 04 43 09.30 | +02 10 19.43 | 1.10147   | 0.53230\(^a\) | 1.01048   |
| II        | M2.1 (A6) | 04 43 10.49 | +02 09 58.53 | 0.95434   | 0.53230\(^a\) | 0.95426   |
|           | M2.2 (A5) | 04 43 09.23 | +02 10 27.22 | 0.95434   | 0.53230\(^a\) | 0.95426   |
| III       | M3.1 (A3) | 04 43 08.57 | +02 10 29.69 | 2.08362\(^b\) | 0.53230\(^a\) | 2.08362\(^b\) |
|           | M3.2 (A2) | 04 43 08.45 | +02 10 18.81 | 2.08318\(^b\) | 0.53230\(^a\) | 2.08318\(^b\) |
|           | M3.3 (A20) | 04 43 09.45 | +02 09 56.88 | ...        | 0.53230\(^a\) | ...        |
|           | M3.4 (--) | 04 43 10.29 | +02 10 23.82 | ...        | 0.53230\(^a\) | ...        |
| IV        | M4.1 (A18) | 04 43 10.20 | +02 09 54.35 | ...        | 0.53230\(^a\) | ...        |
|           | M4.2 (A17) | 04 43 09.97 | +02 09 25.18 | ...        | 0.53230\(^a\) | ...        |
|           | M4.3 (A19) | 04 43 10.00 | +02 10 30.25 | ...        | 0.53230\(^a\) | ...        |
| V         | M5.1 (A7) | 04 43 09.55 | +02 09 57.69 | ...        | 0.53230\(^a\) | ...        |
|           | M5.2 (A16) | 04 43 10.31 | +02 10 25.30 | ...        | 0.53230\(^a\) | ...        |

Notes. Columns (1) and (2): system and arc IDs used in this work followed by the original names used in G98 (in parenthesis). Col. (3) and (4): R.A. and decl. Column (5): spectroscopic redshifts. Column (6): redshifts of lensed sources from G98. Column (7): final redshift values, when applicable, used in the lensing model.

\(^a\) Spectroscopic redshift reported by G98.

\(^b\) There is a weak emission line present in the spectrum of both M3.1 and M3.2 at an observed wavelength of 7156 Å that may be [O III] \( \lambda 5251 \) at \( z = 2.0834 \).
the combination of multiple measurements for a given galaxy is (Figure 6. Flux-calibrated GMOS spectra, in the optical rest frame, of two galaxies with large differences in redshift ($\Delta z = 0.20343$ and $\Delta z = 0.10209$) compared to the values reported by G98. For clarity, the top spectrum has been shifted by $\sim 2$ dex in flux.

It is worth mentioning that galaxies’ redshifts that differed by $\Delta V > 250 \text{ km s}^{-1}$ from the values determined using GMOS are discarded before combining (see below for details about how the combination of multiple measurements for a given galaxy is performed). Some galaxies observed in common with G98 show very large differences (up to $80,000 \text{ km s}^{-1}$). To determine the origin of these large differences in redshift, we first checked the GMOS data. We used the MEGACAM and the GMOS deep images to eliminate any possibility of coordinate mismatch. When this possibility was ruled out (none of the galaxies present coordinate problems), we visually inspected the GMOS spectra of the problematic galaxies. These spectra have high S/N and show clear absorption and/or emission line features characteristic of early- and late-type populations of galaxies. The excellent quality of the GMOS spectra provides high confidence that our measured redshifts are correct and reliable. Unfortunately, G98 do not provide the necessary information about how the redshifts and associated errors were estimated. Given the absence of information, we can only speculate about the erroneous estimations provided by G98 for these galaxies. Possible explanations are: misidentification of absorption/emission lines, low S/N of the spectra, which could impact the cross-correlation results, and velocity mistyping, among others. For the two problematic galaxies observed in common with CFHTMOS, the derived $R$-values (Tonry & Davis 1979) in the CFHTMOS sample are smaller than $R$-values obtained with GMOS, indicating that the measured redshifts are less reliable, due possibly to poor cross-correlation results. For these two galaxies, we used the redshifts derived from GMOS spectra. Figure 6 shows the GMOS spectra of two galaxies observed in common with G98 that show large differences in the redshift estimation (after applied the zero-point correction derived above). The galaxy MS 044314.4+021031 (top spectrum) shows clear emission lines and the measured redshift from the GMOS spectrum is $z = 0.40109$. The galaxy MS 044312.5+021059 (bottom spectrum) shows clear absorption lines. The measured redshifts derived from GMOS and CFHTMOS spectra are $z = 0.19628$ and $z = 0.19728$ ($\Delta V = -150 \text{ km s}^{-1}$), respectively. The redshifts estimated by G98 for these galaxies are $z = 0.19766$ ($\Delta V = 61,169 \text{ km s}^{-1}$) and $z = 0.09419$ ($\Delta V = 30,786 \text{ km s}^{-1}$), respectively. According to G98 the first galaxy (MS 044314.4+021031) is located at the distance of the cluster and the second galaxy (MS 044314.4+021031) is located in the foreground, which is clearly incorrect. The same problem is seen in the remaining 19 galaxies with large differences in redshifts and observed in common with G98.

To construct the final spectroscopic catalog, first we applied the zero-point shifts of $-181 \text{ km s}^{-1}$ and $-150 \text{ km s}^{-1}$ to both G98 and CFHTMOS data sets. Then, for galaxies with multiple measurements, a mean weighted redshift is derived using the relation

$$Z = \frac{\sum_i w_i z_i}{\sum_i w_i} \tag{1}$$

where $z_i$ is the redshift of galaxy $i$, $w_i = 1/\Delta z_i$ is the weighting factor, and $\Delta z_i$ is the redshift uncertainty. The weighting factor $w_i$ came from our internal uncertainties, from CFHTMOS, and from the uncertainties published in G98. The errors in the combined redshifts are calculated following the criteria described in Quintana et al. (2000). In order to minimize the errors in the estimation of the dynamical parameters of the cluster, galaxies with multiple redshifts observed in common between the three data sets with $|\Delta Z| > 0.0008 \left( |\Delta V| > 250 \text{ km s}^{-1} \right)$ are discarded before combining.

The redshifts of 195 out of 204 galaxies from the original sample, corrected to the heliocentric reference frame, the corresponding errors, the magnitudes, and other relevant parameters are shown in Table 3. Our final catalog contains the redshifts of 185 galaxies observed with GMOS and CFHTMOS and in common with G98 and 10 galaxies at the redshift of the cluster from G98 not covered by our observations. The redshifts of these galaxies, corrected by the zero-point shift, are listed at the end of Table 3. We have excluded from the final catalog nine foreground and background galaxies from G98. The final sample contains 30 galaxies with more than one redshift estimation and with differences in velocity $|\Delta V| \leq 250 \text{ km s}^{-1}$: nine galaxies with three measurements and 21 galaxies with two. There are 107 galaxies located inside the GMOS area and 135 galaxies have their spectroscopic redshifts determined for the first time (49 with GMOS and 86 with CFHTMOS). Of these, 44 are located at the redshift of the cluster, increasing by a factor of $\gtrsim 2$ the number of cluster members with known redshifts.

3. Lensing Modeling

The detailed lensing analysis of MS 0440.5+0204 is presented in Paper I. In this section we provide a brief explanation of the method and highlight the main results.

3.1. Weak Lensing

Weak lenses was performed using the methodology described in Foëx et al. (2012). The lensed sources were selecting after removing galaxies located in the red sequence, estimated in the $r''-g''$ diagram, down to a magnitude of $r'' = 23 \text{ mag}$. Galaxies brighter than $r'' = 21 \text{ mag}$ and fainter than $r'' = 25 \text{ mag}$ were also removed. These cuts led to a number density of $\sim 12 \text{ arcmin}^{-2}$.

The shape of the background galaxies was estimated with the software IM2SHAPE (Bridle et al. 2002), as done in Foëx et al. (2012, 2013). The lensing strength (i.e., the factor needed to
## Table 3
Galaxy Redshifts

| Galaxy ID | RA (J2000) | Dec. (J2000) | $r'$ | $g' - r'$ | $z \pm \Delta z$ | R/$\#i$ | Flag | $Z \pm \Delta Z$ | Member? |
|-----------|------------|-------------|------|------------|-----------------|---------|------|-----------------|---------|
| MS 044308.5+021152 | 04 43 08.55 | +02 11 52.4 | 22.27 | 1.15 | 0.19461 ± 0.00019 | 6.0/--- | 1 | 0.19461 ± 0.00027 | Yes |
| MS 044308.7+020839 | 04 43 08.66 | +02 08 39.0 | 19.90 | 1.09 | 0.15994 ± 0.00019 | 5.5/--- | 1 | 0.15994 ± 0.00027 | No |
| MS 044309.9+021142 | 04 43 08.73 | +02 11 42.3 | 22.37 | 1.36 | 0.35688 ± 0.00009 | ---10 | 1 | 0.35688 ± 0.00027 | No |
| MS 044309.0+021028 | 04 43 08.97 | +02 12 08.9 | 21.19 | 1.22 | 0.19716 ± 0.00009 | 13.7/--- | 1 | 0.19716 ± 0.00027 | Yes |
| MS 044309.1+020845 | 04 43 09.10 | +02 08 45.9 | 21.89 | 1.13 | 0.19104 ± 0.00018 | 6.5/--- | 1 | 0.19104 ± 0.00027 | Yes |
| MS 044309.2+021053 | 04 43 09.20 | +02 10 53.0 | 21.32 | 1.27 | 0.19546 ± 0.00013 | 11.3/--- | 1 | 0.19546 ± 0.00027 | Yes |
| MS 044309.3+021350 | 04 43 09.34 | +02 13 50.0 | 19.12 | 1.18 | 0.39989 ± 0.00050 | 5.0/--- | 1 | 0.39939 ± 0.00050 | No |
| MS 044309.4+021037 | 04 43 09.45 | +02 10 36.7 | 21.38 | 1.12 | 0.19369 ± 0.00014 | 6.9/--- | 1 | 0.19369 ± 0.00027 | Yes |
| MS 044309.6+021156 | 04 43 09.58 | +02 11 56.3 | 22.91 | 0.91 | 0.38943 ± 0.0003 | ---4 | 0 | 0.38943 ± 0.00027 | No |
| MS 044309.7+021027 | 04 43 09.67 | +02 10 27.4 | 18.58 | 1.28 | 0.19906 ± 0.00012 | 12.2/--- | 1 | 0.19906 ± 0.00027 | Yes |
| MS 044309.7+021004 | 04 43 09.68 | +02 10 03.9 | 18.54 | 1.23 | 0.19223 ± 0.00014 | 9.1/--- | 1 | 0.19221 ± 0.00027 | Yes |
| MS 044309.7+020815 | 04 43 09.70 | +02 08 15.9 | 22.92 | 1.11 | 0.43362 ± 0.00012 | ---5 | 1 | 0.43362 ± 0.00027 | No |
| MS 044309.7+021023 | 04 43 09.74 | +02 10 22.6 | 18.64 | 1.21 | 0.18780 ± 0.00013 | 10.4/--- | 1 | 0.18781 ± 0.00027 | No |
| MS 044309.9+020947 | 04 43 09.89 | +02 09 46.8 | 21.40 | 0.97 | 0.32986 ± 0.00026 | 5.5/--- | 1 | 0.32986 ± 0.00026 | No |
| MS 044309.9+020199 | 04 43 09.92 | +02 10 19.2 | 17.73 | 1.32 | 0.19873 ± 0.00021 | 8.0/--- | 1 | 0.19831 ± 0.00027 | Yes |
| MS 044310.0+020127 | 04 43 10.04 | +02 10 27.0 | 18.99 | 1.28 | 0.19600 ± 0.00016 | 8.7/--- | 1 | 0.19624 ± 0.00041 | Yes |
| MS 044310.1+021104 | 04 43 10.07 | +02 11 04.0 | 20.20 | 1.34 | 0.19929 ± 0.00014 | 6.3/--- | 1 | 0.19929 ± 0.00027 | Yes |
| MS 044310.1+020941 | 04 43 10.09 | +02 09 41.3 | 22.75 | 0.70 | 0.57586 ± 0.00009 | ---7 | 1 | 0.57586 ± 0.00027 | No |
| MS 044310.1+020121 | 04 43 10.09 | +02 10 21.2 | 17.70 | 1.26 | 0.18908 ± 0.00036 | 2.7/--- | 1 | 0.18857 ± 0.00027 | Yes |
| MS 044310.4+021039 | 04 43 10.36 | +02 10 39.1 | 20.46 | 1.21 | 0.18921 ± 0.00008 | 12.6/--- | 1 | 0.18921 ± 0.00027 | Yes |
| MS 044310.1+021114 | 04 43 11.00 | +02 11 13.7 | 21.44 | 1.21 | 0.18957 ± 0.00023 | 4.2/--- | 1 | 0.18957 ± 0.00027 | Yes |
| MS 044311.1+021206 | 04 43 11.08 | +02 12 06.5 | 21.11 | 1.14 | 0.19340 ± 0.00005 | 19.5/--- | 1 | 0.19340 ± 0.00027 | Yes |
| MS 044311.2+021157 | 04 43 11.19 | +02 11 57.1 | 19.78 | 1.22 | 0.19616 ± 0.00020 | 6.5/--- | 1 | 0.19612 ± 0.00027 | Yes |

*Note.* Columns: (1)—galaxy name; (2)—internal ID; (3)—redshift source; C: CFHTMOS, M: Gemini GMOS, G: Gioia et al. (1998); (4) and (5): R.A. and decl. (J2000.0). The units of R.A. are hours, minutes, and seconds, and the units of decl. are degrees, arcminutes, and arcseconds; (6) and (7)—total $r'$ magnitudes and $g' - r'$ colors measured inside a fixed aperture of $1''$ corrected for galactic extinction ($A(g') = 0.587, A(r') = 0.406$ mag) using the reddening maps of Schlafly & Finkbeiner (2011) and assuming a reddening law of $R_g = 3.1$ ( Fitzpatrick 1999); (8)—individual redshift and associated errors, corrected by the zero-point; (9): $R$-values (Tonry & Davis 1979)—real numbers or the number of emission lines (integer values) used to calculate redshift; (10) flag for galaxies with multiple measurements included in the final weighted redshift: "1"—the individual redshift is included, "0"—the individual redshift is discarded; (11)—final redshift and the associated error used in the analysis, corrected to the heliocentric system. For galaxies with multiple measurements, these values are the mean weighted value; (12)—membership flag. 

(This table is available in its entirety in machine-readable form.)
convert shear into mass) was obtained using the photometric redshifts from the T0004 release of the CFHTLS-DEEP survey that were computed with HYPERZ (Bolzonella et al. 2000). We found an averaged lensing strength $\beta = (D_h/D_m) = 0.66$, where $D_h$ and $D_m$ are the angular-diameter distances lens-source and observer-source, respectively (see Foëx et al. 2013 for a detailed discussion on the $\beta$ factor).

The shear profile was computed in logarithmically spaced annuli, fitted from 100 kpc to 2.5 Mpc, and using two parametric mass models: a singular isothermal sphere (SIS) and a Navarro–Frenk–White (NFW; Navarro et al. 1996, 1997) model. Both models provide a good fit, with a reduced $\chi^2 = 9.1/8$ and $\chi^2 = 8.3/7$ for the SIS and NFW profiles, respectively. For the SIS model we obtain a velocity dispersion of $\sigma_v = 894^{+52}_{-61}$ km s$^{-1}$ and for the NFW profile we obtain $M_{200} = 3.9^{+1.4}_{-0.8} \times 10^{14} M_\odot$ at a radius $r_{200} = 1.46 \pm 0.13$ h$_{70}^{-1}$ Mpc, and a concentration parameter of $c_{200} = 9.5^{+3.8}_{-2.3}$. The concentration parameter is much larger than expected for a cluster having a mass of $M_{200} \sim 4 \times 10^{14} M_\odot$, when the value is compared to the predictions of the $c(M)$ simulation at $z = 0.2$ (e.g., Duffy et al. 2008; Klypin et al. 2016). However, the derived value is in agreement with the SL results (see next section), and in fairly agreement, within the errors, with the $c(M)$ relation of Foëx et al. (2014) obtained by combining stacks of SL galaxy groups and clusters.

Finally, to characterize the 2D shape of the cluster from the WL data, we followed the approach presented in Soucail et al. (2015), which is based on the software LENSENT2 (Marshall et al. 2002), which uses the shape of each background galaxy as a local estimator of the reduced shear. The method, employing an entropy-regularized maximum likelihood, allows us to generate a projected mass map of the cluster.

3.2. Strong Lensing

The three SL models presented in Paper I are performed using the last version of the LENSTOOL ray-tracing code and the Bayesian Markov Chain Monte Carlo (MCMC) method (Jullo et al. 2007). We model the dark matter component of MS 0440.5+0204 using first a single large-scale clump, and then adding smaller-scale clumps, as galaxy-scale perturbations that are associated with individual cluster galaxies (the 13 central galaxies, see inset in Figure 1). We use a single clump description, given the lack of a second luminous subclump and the elliptical pattern of the lensed arcs. In addition, the single cluster model was accurate enough. For the main large-scale clump we adopt an NFW density profile (Navarro et al. 1996, 1997), which is characterized by seven parameters: the center position, $(X, Y)$, the ellipticity $\epsilon$, the position angle $\theta$, the velocity $\sigma_v$, and the scale radius $r_s$.

The velocity dispersion in the line of sight is related to the mass and the density profile through the expression

$$\sigma_v^2 = \frac{2G}{\Sigma(r_s)} \int_{r_s}^{\infty} \left( \sqrt{1 - (r_s/r)^2} \right) M(r) \rho_s(r) \frac{dr}{r},$$

where $\rho_s$ is the characteristic density and $\Sigma(r_s)$ is the characteristic surface mass density. In the case of an isotropic velocity, Equation (2) is equivalent to $\sigma_r^2$ (Equation (7)) used in Verdugo et al. (2011), and represents the velocity dispersion at radius $r_s$ calculated analytically from the mass density profile (see Paper I). In our model, the velocity dispersion $\sigma_v$ is compared with the velocity dispersion obtained in Section 4.2, adding an extra constraint.

The smaller-scale clumps associated with the galaxies are modeled using a pseudoisothermal elliptical mass distribution (PIEMD). A clump modeled with this profile is characterized by the following seven parameters: the center position, $(X, Y)$, the ellipticity $\epsilon$, the position angle $\theta$, and the parameters, $\sigma_0$, $r_{\text{core}}$, and $r_{\text{cut}}$ (see Limousin et al. 2005; Elíasdóttir et al. 2007). The parameters $\epsilon$, $r_{\text{core}}$, and $r_{\text{cut}}$ are scaled as a function of their galaxy luminosities, using as a scaling factor the luminosity $L_*$, associated with the $r'$ magnitude of the central galaxy 100606 (A) (see inset in Figure 1 and Table 3). The parameter $r_{\text{core}}$ is fixed at 0.15 kpc.

Besides, some parameters describing the dark matter halos associated with two individual galaxies, namely 896 (B) and 599 (D) (see insets in Figure 1), were allowed to vary in the optimization procedure, as they perturb some arclets. Our models are computed and optimized in the image plane with 17 free parameters: $(X, Y, \epsilon, \theta, r_s, \sigma_v)$ for the main halo, $(r_{\text{core}}, \epsilon, \theta, r_{\text{cut}}, \sigma_0)$ for the smaller-scale clumps, $(\epsilon, \theta, r_{\text{cut}}, \sigma_0)$ for galaxies 896 (B) and 599 (D), and $(\text{cM})$ for the arc system M5. All the parameters are allowed to vary with uniform priors. As we discuss in Paper I, we tried to include system M4 in the calculations, leaving the redshift as a free parameter, but were unsuccessful in reproducing the configuration. Therefore, we exclude this system from our final models.

The three models, $M_{\text{ens}}$, which uses only the arcs’ positions, $M_{\text{ens-\sigma}}$, where we add the velocity dispersion of the cluster as an additional constraint (see Section 4.2), and $M_{\text{ens-\sigma-mass}}$, which includes the WL mass at $r_s$, reproduce equally well the image positions of the arcs, with similar $\chi^2$/dof and rms image. However, the inclusion of the additional constraints such as the velocity dispersion and the mass in the $M_{\text{ens-\sigma-mass}}$ model gives more stringent constraints than those provided by the other two models. Although the three models reproduce well the SL features presented in MS 0440.5+0204, at large scale the performance of the $M_{\text{ens-\sigma-mass}}$ model is slightly better (see Section 5.1 in Paper I). For our best model, $M_{\text{ens-\sigma-mass}}$, we obtain a mass of $M_{200} = 3.1^{+0.8}_{-0.6} \times 10^{14}$ h$_{70}^{-1} M_\odot$, and a concentration parameter of $c_{200} = 9.3^{+3.2}_{-1.4}$, consistent with the values obtained from the WL analysis.

4. Data Analysis and Discussion

4.1. Completeness of the Spectroscopic Sample

We used the photometric and spectroscopic catalogs constructed from the observations inside the $\sim 0.45 \times 0.14$ region, defined by the CFHTMOS observations, to determine the completeness of the spectroscopic sample. Overall the completeness fractions inside the observed area are $\sim 50\%$ for galaxies brighter than $r' = 20.5$ mag and drop to $\sim 19\%$ for $r' = 21.5$ and to $\sim 13\%$ for $r' = 22.5$. The completeness fractions in the fainter magnitude bins are much higher in the inner 3/5 region of the cluster ($< 0.66$ h$_{70}^{-1}$ Mpc, roughly the GMOS field of view). Indeed, of the galaxies selected for spectroscopy, we were able to determine the redshifts for $\sim 77\%$ of those brighter than $r' = 20.5$ and for $\sim 56\%$ and $\sim 38\%$ at $r' = 21.5$ and at $r' = 22.5$, respectively.

In addition to the above completeness estimation, we also compared the radial distribution of the galaxies with measured redshifts to the galaxies selected for spectroscopy based on the color–magnitude relation (bottom panel in Figure 8). We
calculated the completeness fraction comparing the ratio of the number of galaxies with measured redshifts to the number of galaxy candidates without, for six different radial bins of 1.5 width (~292 h\(^{-1}\) Mpc) and centered at the cluster center. Table 4 shows the spectroscopic completeness fractions for the six radial bins and for different magnitude intervals. The radial distribution shows that the completeness fraction decreases toward the outskirts of the cluster as expected. In particular, for the 4/5 bin, corresponding to a physical radius of \(\sim 0.88\) h\(^{-1}\) Mpc (roughly \(\sim 0.5 \times r_{200}\) see Section 4.3 below), the completeness fractions are \(\sim 70\%\) at \(r' = 20.5\), \(\sim 50\%\) at \(r' = 21.5\), and \(\sim 38\%\) at \(r' = 22.5\). Based on the above results, we believe that our spectroscopic sample represents well the galaxy population in MS 0440.5+0204.

### Table 4

| Magnitude (bin) | \(f(r')\) |
|----------------|----------|
| (1) 16.5–17.5 | 1.00     |
| (2) 17.5–18.5 | 1.00     |
| (3) 18.5–19.5 | 0.83     |
| (4) 19.5–20.5 | 0.89     |
| (5) 20.5–21.5 | 0.74     |
| (6) 21.5–22.5 | 0.54     |

### 4.2. Redshift Distribution

The histogram of the redshift distribution for the 195 galaxies in the field of MS 0440.5+0204 (\(\sim 0.5 \times 0.74\) Mpc\(^{-1}\)) is shown in Figure 7. Ninety-six galaxies lie in the redshift interval 0.183 \(\leq z \leq 0.209\) (within \(\pm 4000\) km s\(^{-1}\) around \(z = 0.196\), gray shaded region in the figure). We calculated the average redshift, the one-dimensional line-of-sight velocity dispersion, and the number of member galaxies of the cluster using the robust bi-weight estimators of central location (\(C_B\)) and scale (\(s_B\)) of Beers et al. (1990). An iterative procedure was used to determine the location and scale with the program ROSTAT and a 3\(\sigma\) clipping algorithm was applied to remove outliers. The procedure was repeated until the velocity dispersion converged to a constant value (after two iterations). The best estimates of the location (\(\bar{z}\)) and scale (\(s_{los}\)) are shown in Table 5. The table also shows the number of member galaxies, \(N_{mem}\) the maximum radius at which we have spectroscopic members, \(r_{max}\), and other relevant dynamical parameters derived in Section 4.3. It is worth noting that the calculated \(s_{los}\) is lower than the value reported by G98 (872\(\pm 123\) km s\(^{-1}\)) and the value derived in Paper I (see Section 3.1), but agrees well, within the quoted uncertainties.

The histogram of the redshift distribution of member galaxies is shown in the upper panel of Figure 8. The open histogram shows the distribution of spectroscopically confirmed member galaxies inside the surveyed area. Sixty-seven member galaxies (\(\sim 68\%\) of the sample) are located within a radius of 0.5 \(\times r_{200}\) (gray histogram), roughly the region covered by the GMOS observations. Note that the central elliptical galaxy “C” (894) is formally rejected as a cluster member by the 3\(\sigma\) clipping algorithm. The galaxy is at the limit of the redshift distribution in Figure 8 and it is close to the bright elliptical galaxy “A” (100606), and could be a member of a small group of galaxies located behind the cluster.

### Table 5

| Parameter | Values |
|-----------|--------|
| R.A.(2000) | 04h43m10s+04°43′10+4° |
| Decl.(2000) | +02°10′20.21'' |
| \(Z\) | 0.199929-0.00003 |
| \(N_{mem}\) | 94 |
| \(s_{los}\) (km s\(^{-1}\)) | 716.63 |
| \(r_{max}\) (h\(^{-1}\) Mpc) | 2.59 |
| \(s_{200}\) (km s\(^{-1}\)) | 807.56 |
| \(r_{200}\) (h\(^{-1}\) Mpc) | 1.73 |
| \(M_{200}\) (10\(^{14}\) h\(^{-2}\) M\(_{\odot}\)) | 3.66 |
| \(M_{K}\) (<200) (10\(^{11}\) h\(^{-2}\) M\(_{\odot}\)) | 2.99 |

Notes. All quoted errors are at the 68% confidence level (1\(\sigma\)).

\(^{*}\) Includes the galaxy “C” (894) (see Section 4.2).

Although it is not formally a member of the cluster, galaxy “C” (894) has a line-of-sight velocity (see Table 7) below the escape velocity of the cluster of \(v_{esc} = 2334\pm 443\) km s\(^{-1}\), calculated using the \(M_{200}\) and \(r_{200}\) determined in Section 4.3. Therefore, hereinafter, galaxy “C” (894) is included in the analysis, thus extending the number of cluster galaxies to 94. The lower panel in Figure 8 shows the color–magnitude diagram (CMD) of all galaxies brighter than \(r' = 24\) mag detected inside an area of \(0.5 \times 0.5\) (~5.8 x 5.8 h\(^{-1}\) Mpc\(^2\)) the majority of member galaxies are located inside the region defined by the linear CMD relation for early-type galaxies in clusters, i.e., the red cluster sequence (RCS) (Gladders et al. 1998; Gladders & Yee 2000). Using a standard linear regression plus an iterative 3\(\sigma\) clipping algorithm to remove outliers, we have determined an RCS slope of \(-0.030 \pm 0.006\), with an intercept of 1.835 ± 0.116 (red solid line in the CMD in Figure 8). The number of galaxies following the RCS and within \(\pm 1\sigma\) (dashed lines) is 81 (80% of the sample), while the

\(^{12}\) A cluster member can be defined as a galaxy with line-of-sight velocity lower than the escape velocity, where \(v_{esc} = (M_{200}/10^{14} h^{-1} M_{\odot})^{1/2}/(r_{200}/h^{-1} \text{ Mpc})^{1/2}\) (Diaferio 1999).
numbers of galaxies bluer and redder than the slope are eight (9%) and five (5%), respectively. This is not surprising since the result is a consequence of how the galaxies were selected for spectroscopic follow-up. We used the information provided by the CMD to analyze the spatial distribution of the member galaxies and the possible connection of MS 0440.5+0204 with other nearby structures. This point is discussed in detail in Section 4.5.

4.3. Cluster Mass

We have computed the dynamical mass of the cluster using the $\sigma$–$M_{200}$ scaling relation of Munari et al. (2013) obtained from zoomed-in hydrodynamical simulations of DM halos calibrated using DM particles and taking into account prescriptions for cooling, star formation, and feedback from active galactic nuclei:

$$\sigma_{1D} = A_{1D} \left[ \frac{h(z) M_{200}}{10^{15} M_\odot} \right]^{\alpha} \quad (3)$$

where $\sigma_{1D}$ is the one-dimensional (1D) velocity dispersion, $A_{1D} = 1177 \pm 4.2 \ km \ s^{-1}$, $\alpha = 0.364 \pm 0.002$, $h(z) = H(z)/70$ km s$^{-1}$ Mpc$^{-1}$, and $M_{200}$ is the mass within $r_{200}$. For our calculation, we assume $M_{200}$ computed within $r_{200}$ as a proxy for the 1D velocity dispersion. The values for the mass $M_{200}$, the radius $r_{200}$, the number of member galaxies inside $r_{200}$, $N_{500}$, and $r_{500}$ are listed in Table 5.

We also estimated the total X-ray mass at radius $r_{200}$ assuming that the gas is isothermal and in hydrostatic equilibrium with a density distribution that follows a circular single $\beta$-model. The X-ray mass at any radius can be computed using the following relation (Evrard et al. 1996):

$$M_X(<r) = 1.13 \times 10^{14} \beta \frac{T_X}{\text{keV Mpc}} \frac{r}{(r/r_c)^2} \frac{h_{70}^{-1} M_\odot}{[1 + (r/r_c)^2]} \quad (4)$$

where $T_X$ is the isothermal X-ray cluster temperature, $r_c$ is the core radius in the $\beta$-model, and $\beta$ is the model parameter. To calculate the X-ray mass we assume an average values of $\beta = 0.45 \pm 0.03$, $r_c = 0.03 \pm 0.01 \ h_{70}^{-1} \text{Mpc}$, and $T_X = 3.4 \pm 0.4 \text{keV}$ (Shan et al. 2010; Mahdavi et al. 2013). The resulting X-ray mass is given in Table 5.

We also computed the virial mass following the prescription of Heisler et al. (1985). Using the classical estimator for the mass and the radius, we obtained a virial mass of $M_{\text{vir}} = 3.75^{+0.38}_{-0.23} \times 10^{14} \ h_{70}^{-1} M_\odot$ at a radius of $r_{\text{vir}} = 1.34^{+0.11}_{-0.08} \ h_{70}^{-1} \text{Mpc}$. It is important to remember that the calculation of virial mass assumes that the system is self-gravitating and the galaxies have equal masses, and it relies on the velocities of the galaxies, the mean velocity of the system, and the projected separation between the galaxies (Equation 4 in Heisler et al. 1985).

The estimated $M_{200}$ mass is in good agreement, within the uncertainties, with other mass estimates. The mass is $\sim 18\%$ larger than the X-ray mass and the mass derived from our best-fit lensing model $M_{\text{lens}} - M_{\text{mass}}$, $\sim 6\%$ smaller than $M_{200}$ derived from weak lensing, and $\sim 8\%$ smaller than the virial mass (see also Section 5.4 in Paper I).

4.4. Substructures

In this section we analyze the dynamical state of MS 0440.5+0204 by examining the redshifts and the projected distributions of the member galaxies.

4.4.1. Line-of-sight Substructures

The histogram in Figure 8 shows two prominent peaks in the distribution, one located at $z \sim 0.196$ and the other at $z \sim 0.199$. The histogram also shows a prominent tail toward lower redshifts (0.0188 < $z$ < 0.192). This is more evident for the 67 galaxies (gray histogram in Figure 8) located inside the radius $0.5 \times r_{200}$ (the central overdensity in Figure 10). A first indication of the existence of a multimodal distribution in the redshift space using all member galaxies is provided by the different statistical tests implemented in the ROSTAT program. All statistical tests, such as the Watson $U^2$ and Anderson–Darling $A^2$, reject the hypothesis of a single Gaussian

---

13 $r_{200}$ is the radius where the overdensity is 200 times the critical density of the universe and is defined as $r_{200} = (\sqrt{3} \sigma_8)/(10 \ H(z))$ (Carlbarg et al. 1997).
distribution at a significance level of 94% on average. Note that some member galaxies distributed toward the east and outside the $0.5 \times r_{200}$ region seem to be located in a filament (see Figure 10). Thus, this structure, as well as others located west and southwest (see Section 4.4.2), could bias the 1D analysis and hence provide a wrong interpretation of the results. To have a more realistic picture of the dynamical state of the cluster, we have restricted the 1D analysis to the central $0.5 \times r_{200}$ region of the cluster (i.e., radius $r \leq 0.866 h_{70}^{-1}$ Mpc).

We used the Gaussian mixture modeling analysis implemented in the GMM code by Muratov & Gnedin (2010) to investigate in detail the structures identified in Figure 8 and quantify the significance of the multimodal distribution. The GMM code fits different Gaussian mixture modes and compares them to a unimodal distribution. The robustness in the multimodal distribution provided by GMM is based on three parameters: the kurtosis of the distribution ($k$), the maximum log-likelihood of the model convergence ($\log \lambda$), and the separation of the means relative to their widths (DD). A deviation from a unimodal distribution is statistically significant when DD $> 2$, $k < 0$, and the log-likelihood values are greater than that for a unimodal fit. The errors of the output parameters are estimated using nonparametric bootstrapping, and the confidence intervals at which an unimodal distribution can be rejected are calculated using parametric bootstrapping.

We considered whether the redshift distribution of the 67 galaxies is consistent with two and three components. In the first case, a unimodal distribution is marginally rejected, at a confidence level of 87% (p-value of 0.13), with no clear separations (DD = 2.93 ± 1.17). If we assume that the redshift distribution in Figure 8 is indeed trimodal, the GMM test rejects a unimodal distribution at a confidence level of 98.5% (p-value 0.015), with a clear separation between the peaks (DD = 4.26 ± 1.27). Therefore, a model with three components is statistically more significant than a model with two components. Table 6 shows the results from the GMM test considering a trimodal distribution in the redshift space. The histogram of the redshift distribution for the galaxies assigned to each of the three line-of-sight structures found by GMM is shown in Figure 9.

Another interesting feature is the location of the six components of the BCG (red arrows in Figure 8). These galaxies are grouped in pairs and close, in redshift, to the mean redshifts derived for the structures S1, S2, and S3. The main parameters of the six central ellipticals (nuclei) are summarized in Table 7. The relative position (columns 4 and 5) is measured with respect to the center of the X-ray emission located at $04^h 43^m 09^s 85^s$, $+02^\circ 10' 20'' 3$. The absolute $r'$ magnitudes (column 8) is corrected for galactic extinction and $K$-corrected. The line-of-sight velocity, i.e., the radial velocity offset from the median redshift of the cluster, for each central elliptical galaxy shown in column 3 is calculated as follows:

$$\Delta V_i = \frac{z_i - \bar{z}}{1 + \bar{z}} c$$

where $z_i$ is the redshift of galaxy $i$, $\bar{z}$ is the average redshift of the cluster, and $c$ is the speed of light. The two brightest components, “A” and “B,” have a difference in velocity of ~2600 km s$^{-1}$. Moreover, the pairs “A–C,” “E–F,” and “B–D” have differences in velocity between them of 192 km s$^{-1}$, 159 km s$^{-1}$, and 188 km s$^{-1}$, respectively. The small line-of-sight velocity separation between the three pairs and the location of the galaxies in the histogram indicate that these galaxies (in pairs) are associated with the line-of-sight structures S1, S2, and S3, respectively. Interestingly, the two faintest components “E” and “F” are located at only ±100 km s$^{-1}$ from the average redshift of the cluster.

### 4.4.2. Galaxy Projected Distribution

Figure 10 shows an adaptive kernel density map (Silverman 1986) of the cluster members. The member galaxies are predominantly distributed along the east–west direction. The projected distribution shows at least four overdensities. The galaxies in the northeast overdensity are distributed in a filament that extends for ~2 $h_{70}^{-1}$ Mpc in the direction of another structure, the poor cluster of galaxies ZwCL 0441.1 +0211 (R.A. = $04^h 43^m 02^s 2$, decl. = $+02^\circ 16' 33''$, Zwicky et al. 1965). This distribution is striking, because it suggests that the two structures might be connected. We return to this point in Section 4.5. Another cluster in the area is CLJ 0440 +0202. However, this cluster is a background structure at redshift $z = 1.1$ (Stern et al. 2003).

Figure 10 shows three other overdensities located ~7' southwest, ~10' northwest, and ~10' west from the cluster center. These overdensities are small groups of 3–9 galaxies that might be falling into the cluster. Our interpretation is based on the location of the galaxies belonging to these groups in the projected phase diagram (see Figure 13) and on the analysis presented in Section 4.4.3.

The central region of the cluster (inset in Figure 10) shows at least three other overdensities. The galaxies linked to the
The size of the image is 0.5 × 0.5 (∼5.2 × 5.2 Mpc² at the cluster distance). The colored circles and the bar denote the positions and redshifts of the member galaxies. The size of each circle is proportional to the luminosity of the galaxies. The GMOS field of view is represented by a dashed square at the center of the image. The large green solid and dashed circles represent the radii r₂₀₀ and 0.5 × r₂₀₀, respectively. The big pluses indicate the locations of the two known clusters inside the surveyed area. The inset in the lower left corner shows the central 0.5 × r₂₀₀ region of the cluster with the Chandra X-ray emission (brown contours) and the adaptive kernel density map (gray contours) overlaid. The different symbols show the locations of the galaxies linked to the structures S1 (blue pluses), S2 (green crosses), and S3 (red stars).

![Projected galaxy density map of the 94 cluster members. The adaptive kernel density map is superimposed on the r' band CFHT image (black contours).](image)

**Figure 10.** Projected galaxy density map of the 94 cluster members. The adaptive kernel density map is superimposed on the r' band CFHT image (black contours). The size of the image is 0.5 × 0.5 (∼5.2 × 5.2 Mpc² at the cluster distance). The colored circles and the bar denote the positions and redshifts of the member galaxies. The size of each circle is proportional to the luminosity of the galaxies. The GMOS field of view is represented by a dashed square at the center of the image. The large green solid and dashed circles represent the radii r₂₀₀ and 0.5 × r₂₀₀, respectively. The big pluses indicate the locations of the two known clusters inside the surveyed area. The inset in the lower left corner shows the central 0.5 × r₂₀₀ region of the cluster with the Chandra X-ray emission (brown contours) and the adaptive kernel density map (gray contours) overlaid. The different symbols show the locations of the galaxies linked to the structures S1 (blue pluses), S2 (green crosses), and S3 (red stars).

| Galaxy | V_heli | ΔV | X  | Y  | X  | Y  | M_r' |
|--------|--------|----|----|----|----|----|------|
| A (100606) | 56533 ± 80 | −1845 | −3.69 | +1.01 | −11.99 | +3.27 | −22.84 |
| B (896) | 59453 ± 80 | +597 | −1.09 | −1.08 | −3.53 | −3.49 | −22.80 |
| C (894) | 56303 ± 80 | −2037 | +1.69 | +2.26 | +5.48 | +7.35 | −21.89 |
| D (599) | 59678 ± 80 | +785 | +2.70 | +7.15 | +8.77 | +23.23 | −21.95 |
| E (616) | 58831 ± 123 | +77 | −2.76 | +6.71 | −8.96 | +21.80 | −21.55 |
| F (K1) | 58641 ± 89 | −82 | −1.36 | +1.54 | −4.42 | +4.99 | −20.29 |

**Note.** Columns: (1) central component identification; (2) and (3) heliocentric radial velocity and line-of-sight velocity in units of km s⁻¹; (4)–(7) relative positions of the galaxies with respect to the X-ray center in arcseconds and kiloparsecs; (8) absolute magnitude in r' corrected for galactic extinction (A(r') = 0.406 mag) and K-corrected.

The large green solid and dashed circles represent the radii r₂₀₀ and 0.5 × r₂₀₀, respectively. The big pluses indicate the locations of the two known clusters inside the surveyed area. The inset in the lower left corner shows the central 0.5 × r₂₀₀ region of the cluster with the Chandra X-ray emission (brown contours) and the adaptive kernel density map (gray contours) overlaid. The different symbols show the locations of the galaxies linked to the structures S1 (blue pluses), S2 (green crosses), and S3 (red stars).
overdensities shown in Figure 10: the group G1 located northeast with 17 galaxies, the cluster core with 67 galaxies, and the groups G2 and G3 located west with 15 and 6 galaxies, respectively.

We repeated the MDGMM test using the 67 galaxies located in the central region of the cluster and assigned to the line-of-sight structures S1, S2, and S3, assuming the same number of initial components. In this case, both BIC and AIC converged to the same minimum of three components. The inset in Figure 11 shows the locations and the galaxies assigned to these three subcomponents. It is remarkable to see how well the galaxies associated with these subcomponents follow the galaxy density map in the inner region of the cluster and at large scale.

Motivated by the results in the redshift distribution (Figure 9) and by the existence of different subcomponents in the projected distribution (Figures 10 and 11), we used the Dressler–Shectman (DS) test (Dressler & Shectman 1988) to statistically evaluate the likelihood of substructures using the information about the spatial and kinematical positions of galaxies. The DS test takes a number $N_{\text{nn}}$ of neighbors from each galaxy in the projection, estimates the local mean velocity and velocity dispersion of the subsample, and compares these with the global mean velocity and velocity dispersion of the whole sample. The final values are then summed to obtain $\Delta = \sum_i^N \delta_i$, where $\Delta/N > 1$ is an indicator of substructure. A graphical representation of the DS test (Figure 12) reveals two substructures: the main cluster at the center of the figure and the eastern substructure (the largest circle in the figure) corresponding to the galaxies in group G1 in Figure 11. Using the 10 nearest neighbors ($N_{\text{nn}} \approx \sqrt{N}$), we obtained $\Delta/N = 1.14$. We used the Monte Carlo technique to find the significance of the DS test. We recalculated the statistic by randomly shuffling 10,000 times the velocities of the galaxies among the cluster members, while holding the positions fixed. The result of the statistic shows $\Delta/N > 1$ for ~60% of the trials, implying that there is some evidence for substructures that are perturbing the cluster, in agreement with 1D and 2D results presented above. Apart from the eastern group G1, the DS test does not reveal the substructures at the center of the cluster. Therefore, the strongest evidence of a merging event comes from three sources: the redshift distribution (Figure 9), the galaxy projected distribution (Figures 10 and 11), and the location of the different structures in the projected phase-space diagram (Figure 13).

The cluster shows a complex structure and appears to be dynamically active, accreting galaxies and groups from their neighborhoods. This is not surprising, since there is much evidence that clusters are still accreting substructures at intermediate and low
Project the phase-space diagram for all spectroscopically confirmed member galaxies of MS 0440.5+0204. We can see that the different overdensities/groups and line-of-sight structures detected in Figures 9–11 occupy distinct locations in the phase-space diagram.

The galaxies lying in the lower region and at $r/r_{200} > 0.5$ in Figure 13 (brown triangles) are part of the group G3 located to the west. On the other hand, galaxies located in the upper region and at $r/r_{200} > 0.5$ (blue inverted triangles) are part of the group G1 located to the east. Roughly 50% of galaxies associated with the group G2 (green squares) lie in the virialized and intermediate regions and at $r/r_{200} < 0.5$, where the backsplash population reside, indicating that these galaxies could have been recently accreted or they could have been accreted at an earlier time and then rebounded outward (e.g., Balogh et al. 2000; Gill et al. 2005; Rhee et al. 2017). The remaining galaxies in the group G2 and galaxies in the groups G1 and G3 are distributed mainly in the infalling region ($(r/r_{200}) \times (\Delta V/\sigma) > 0.4$), suggesting that these galaxies have been recently accreted.

The galaxies associated with the line-of-sight structures S1, S2, and S3 show large $\Delta V/\sigma$ values as expected based on the analysis presented in Section 4.4.1. The galaxies in the structure S2 occupy the inner central region in the phase-space diagram (inside the $0 < (r/r_{200}) \times (\Delta V/\sigma) < 0.1$ bin) with a narrow range of $\Delta V/\sigma$ values, indicating that they were accreted during formation of the cluster (e.g., Haines et al. 2012; Noble et al. 2013). A large fraction of the galaxies in the structures S1 and S3 occupy the intermediate region in the phase-space diagram ($0.1 < (r/r_{200}) \times (\Delta V/\sigma) < 0.4$, the backsplash region), but with large values of $\Delta V/\sigma$. This can be interpreted as showing that the galaxies in S1 and S3 have already passed through the core of the cluster, but have not yet had time to join the virialized population. Based on these results, it is likely that the cluster is experiencing a strong merging process along the line of sight.

Figure 14. Projected galaxy density map of 1328 galaxies brighter than $r' = 24$ mag and distributed in the RCS in Figure 8 (dark red contours) superposed on a grayscale image of the density map of member galaxies (dashed black contours). The size of the image and the meaning of the colored circles and the color bar are the same as in Figure 10. The dark green and blue contours are from Paper I and correspond to the WL 2D and SL mass contours, respectively.
Moreover, the strong merging event could explain the presence of the diffuse extended symmetric envelope (e.g., Dubinski 1998) and the high concentration value obtained in our lensing analysis (Paper I).

4.5. The Environment around MS 0440.5+0204 and the Connection with Other Structures

The analysis presented in Section 4.4.2 suggests that MS 0440.5+0204 might be connected to the poor cluster of galaxies ZwCL 0441.1+0211 through the galaxies located east from the cluster (group G1 in Figure 11). To further investigate this possibility, we have used the NASA/IPAC Extragalactic Database (NED) to search for information about the redshift of the ZwCL 0441.1+0211 cluster and the galaxies belonging to it. Unfortunately, the NED database does not provide any information on the redshift of the cluster and its member galaxies. The cluster is listed as an X-ray source in the ASCA Medium Sensitive Survey (Ueda et al. 2001), but the redshift of the cluster is not provided. We also used the Sloan Digital Sky Survey Data Release 12 database to search for any information about this cluster, but unfortunately the region is not in the SDSS footprints.

In the absence of redshift information on the galaxies in the ZwCL 0441.1+0211 cluster, we used an alternative approach to investigate whether there is a potential connection between the two clusters. If we assume that the galaxies in ZwCL 0441.1+0211 are located close in redshift to MS 0440.5+0204, then one could expect that the early-type galaxies in ZwCL 0441.1+0211 share the same location in the color–magnitude relation of Figure 8. Based on this assumption, we have analyzed the projected density distribution of all galaxies lying in the RCS and within ±1 Mpc from the best fit shown in the bottom panel of Figure 8.

Figure 14 shows the adaptive kernel density map of a sample of 1328 galaxies located in the RCS and brighter than r′ = 24. The galaxy density map (thick dark red contours) shows two prominent peaks, one coincident with the center of MS 0440.5+0204 and another near the position of ZwCL 0441.1+0211. Remarkably, the contours of the density map follow the same distribution pattern as the contours of the density map of member galaxies in Figure 10 (thin dashed black contours), suggesting that the two structures might be connected. The figure also shows the 2D mass map from the SL model (blue lines) and the 2D mass map from weak lensing (green lines) from Paper I. The direction of the contours in the SL 2D mass map is consistent with the direction of the contours of the 2D WL signal and with the direction of the contours in the density maps for member galaxies and the galaxies lying in the RCS. In addition, the elongation and position angle of the 2D SL mass map point northeast, where the ZwCL 0441.1+0211 cluster is located. As discussed in Paper I, this elongation is likely produced by the influence of the ZwCL 0441.1+0211 cluster. We refer the reader to Paper I for a detailed discussion about the 2D mass maps obtained from the lensing models.

To confirm the above results, we have used the magnitudes and colors of the galaxies located in the RCS and inside a circle of 3′ radius (∼585 h70−1 kpc at the redshifts of MS 0440.5+0204) from the high-density peak in Figure 15 to analyze the color–magnitude relation of these galaxies. The selected galaxies are shown in the top panel of Figure 15. It is important to mention that the selection of the galaxies in MS 0440.5+0204 is independent of their membership. We used a standard linear regression plus an iterative 3σ clipping algorithm to determine the slope and the intercept of the two populations. For MS 0440.5+0204, we obtained a slope of −0.032 ± 0.005 with an intercept of 1.875 ± 0.107. In the case of ZwCL 0441.1+0211, we obtained a slope of −0.030 ± 0.007 and an intercept of 1.838 ± 0.147. The best fits from the linear regression are shown in the CMD in the bottom panel of Figure 15 (red and blue dashed lines). We can see that values for the intercepts and the slopes are similar, within the errors. This result reinforces our finding that ZwCL 0441.1+0211 and MS 0440.5+0204 are practically at the same distance. Moreover, the distribution of the galaxies inside the filament (group G1) and the elongation seen in the 2D SL mass map strongly support the idea that these two clusters might be connected. However, to prove this statement it is necessary to determine the redshifts of the galaxies in the area of ZwCL 0441.1+0211.

5. Summary and Conclusions

In this work we have presented a detailed kinematical and dynamical analysis of the SL galaxy cluster MS 0440.5+0204, a massive structure located at z = 0.1959. The analysis is based on new spectroscopic data obtained for the most prominent arc systems in the cluster core and hundreds of galaxies observed in a wider area on the sky. Our main results and conclusion of this study are summarized in the following paragraphs.
We have determined, for the first time, the spectroscopic redshifts for the gravitational arc systems M1, M2, and M3, and confirmed the redshift for the arc system S1, which is in good agreement with the redshift obtained by G98. We have measured the spectroscopic redshifts for 185 galaxies observed with GMOS and CFHTMOS inside an area of $\sim0.045 \times 0.14$ in R.A./decl. ($\sim 5.3 \times 1.6 \ h_{70}^{-2} \ Mpc^2$ at the distance of the cluster). The redshift catalog was supplemented with 10 additional galaxies located at the redshift of the cluster from G98 and not covered by our observations, increasing the sample to 195 galaxies with confirmed redshifts (Section 2.4). We have estimated new redshifts for 135 galaxies, of which 44 are at the distance of MS 0440.5+0204, increasing the number of cluster members by a factor of $\sim 2$. Using the robust bi-weight estimators of Beers et al. (1990), we determined an average redshift for the cluster of $0.19599 \pm 0.00033$ and a line-of-sight velocity dispersion of $711 \pm 51 \ km \ s^{-1}$ for 94 confirmed member galaxies. The velocity dispersion is slightly lower, but in agreement within the uncertainties, than the values reported by G98 (Section 4.2) and derived in Paper I using the SIS model profile (Section 3.1). We have computed the mass of the cluster using the $\sigma-M_{200}$ scaling relation of Munari et al. (2013). We determined a dynamical mass $M_{200} = 3.66 \pm 0.59 \times 10^{14} \ h_{70}^{-1} \ M_{\odot}$ at $r_{200} = 1.73 \pm 0.14 \ h_{70} \ Mpc$ (Section 4.3). The dynamical mass is in very good agreement with the total mass inferred from the WL analysis ($M_{200} = 3.97 \pm 0.4 \times 10^{14} \ h_{70}^{-1} \ M_{\odot}$, Paper I) and from X-rays ($M_X = 3.80 \pm 0.46 \times 10^{14} \ h_{70}^{-2} \ M_{\odot}$).

The cluster shows several structures along the line of sight and in the spatial direction. We find that the redshift distribution of the galaxies in the inner $r \sim 0.86 \ h_{70}^{-1} \ Mpc$ of the cluster ($0.5 \times 2_{FWHM}$) is at least trimodal at the 98.5% confidence level, and with three well defined structures. These structures, named S1, S2, and S3, basically form the cluster core. Additional evidence of dynamical activities is given by the groups G1 and G3, which are likely falling into the cluster core.

The complex redshift distribution of member galaxies in the cluster core and along the line of sight, and the presence of several structures in the galaxy density maps and in the WL mass map, reveal that MS 0440.5+0204 is dynamically active. The central region of the cluster might be experiencing a merging process along the line of sight. The central elliptical galaxies might eventually merge to form a massive galaxy at the cluster core. Additional evidence of dynamical activities is given by the groups G1 and G3, which are likely falling into the cluster core.

We would like to thank the anonymous referee for constructive and helpful comments. E.R.C. acknowledges the hospitality of the Observatorio Astronómico Nacional of the Universidad Nacional Autónoma de México in Ensenada, where this work was partially done. This research has been carried out thanks to PROGRAMA UNAM-DGAPA-PAPIIT IA102517. V.M. acknowledges the partial support from Centro de Astrofísica de Valparaíso, a program of NSF’s NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation, on behalf of the Gemini Observatory partnership: the National Science Foundation (United States), National Research Council (Canada), Agencia Nacional de Investigación y Desarrollo (Chile), Ministerio de Ciencia,
