THE MASSIVE AND DISTANT CLUSTERS OF WISE SURVEY. II. INITIAL SPECTROSCOPIC CONFIRMATION OF $z \sim 1$ GALAXY CLUSTERS SELECTED FROM 10,000 deg$^2$

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ABSTRACT

We present optical and infrared imaging and optical spectroscopy of galaxy clusters which were identified as part of an all-sky search for high-redshift galaxy clusters, the Massive and Distant Clusters of WISE Survey (MaDCoWS). The initial phase of MaDCoWS combined infrared data from the all-sky data release of the Wide-field Infrared Survey Explorer (WISE) with optical data from the Sloan Digital Sky Survey to select probable $z \sim 1$ clusters of galaxies over an area of 10,000 deg$^2$. Our spectroscopy confirms 19 new clusters at $0.7 < z < 1.3$, half of which are at $z > 1$, demonstrating the viability of using WISE to identify high-redshift galaxy clusters. The next phase of MaDCoWS will use the greater depth of the AllWISE data release to identify even higher redshift cluster candidates.

Key words: galaxies: clusters: individual – galaxies: distances and redshifts – galaxies: evolution

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Studies of massive clusters of galaxies have provided the first evidence for the existence of dark matter (Zwicky 1937), shown the importance of environment in galaxy evolution (Dressler 1980), and currently can provide competitive constraints on cosmological parameters (Allen et al. 2011; Benson et al. 2013). Much of the power of such studies derives primarily from the extreme cluster masses ($M > 10^{14} M_\odot$). The largest area surveys can identify the rarest, most massive clusters. The ROSAT All-Sky Survey resulted in catalogs of very massive galaxy clusters at low to moderate redshifts (Ebeling et al. 1998, 2001, i.e., the BCS at $z < 0.3$ and MACS at $z < 0.7$). More recently, the Planck mission has provided an all-sky catalog of very massive galaxy clusters at $z < 1$ (Planck Collaboration et al. 2013), while the South Pole Telescope and Atacama Cosmology Telescope detect high-mass clusters reaching even above $z > 1$ over several thousand square degrees (Williamson et al. 2011; Marriage et al. 2011; Reichardt et al. 2013). However, until recently, no surveys were capable of identifying massive clusters at $z \gtrsim 1$ over the full extragalactic sky.

The primary means of identifying clusters of galaxies include optical/infrared searches for galaxy overdensities, X-ray searches that detect the hot gas of the intracluster medium, and millimeter-wave searches that rely on the Sunyaev–Zel’ dovich (SZ) effect. The latter technique is nearly mass-limited due to the weak redshift dependence of the detection signal, which makes SZ surveys ideal for cosmological tests based upon evolution of the cluster mass function. Similar to the SZ, surveys at X-ray wavelengths have the advantage of being able to estimate cluster masses directly from their data (if the cluster redshifts are known). However, the X-ray signal drops dramatically with redshift, and X-ray surveys so far have not been able to cover very large areas to the depth necessary to find large numbers of very massive clusters at high redshifts. In the future, eROSITA (Predehl et al. 2010) should provide an upgrade to the prospects of large-area X-ray cluster surveys.

Using infrared imaging, cluster searches that detect galaxy overdensities provide the greatest reach in redshift and mass sensitivity at high redshift, extending to $z \sim 2$ and below $M \sim 10^{14} M_\odot$ (e.g., Eisenhardt et al. 2008; Papovich et al. 2010; Brodwin et al. 2011; Stanford et al. 2012; Zeimann et al. 2012; Galametz et al. 2012; Muzzin et al. 2013; Wylezalek et al. 2013). The limiting factor for Spitzer is the relatively limited areas (e.g., $\sim 100$ deg$^2$, Ashby et al. 2013) for which it is feasible to obtain moderate-depth IRAC imaging. The Wide-field Infrared Survey Explorer mission (WISE; Wright et al. 2010) offers the means to find massive clusters at $z > 1$ over the full extragalactic sky using methods pioneered with the IRAC camera on board the Spitzer Space Telescope. We are conducting the next generation high-redshift cluster search using WISE, the Massive and Distant Clusters of WISE Survey (MaDCoWS). We have already published the first $z \sim 1$ cluster confirmed from MaDCoWS (Gettings et al. 2012). Here we report on the initial results of follow-up observations to confirm an initial sample of WISE-selected galaxy clusters selected to be at $z \sim 1$. M. Brodwin et al. (in preparation) will present Sunyaev–Zel’dovich (SZ) measurements and cluster masses for some of the clusters in this paper.

2. WISE SELECTION OF CLUSTER CANDIDATES

The key aspect of the WISE mission enabling detection of high-redshift galaxy clusters is the excellent photometric sensitivity at 3.4 and 4.6 μm (W1 and W2, respectively). The WISE All-Sky Data Release achieves 5σ sensitivity limits better than 0.07 and 0.1 mJy in unconfused regions in W1 and W2. These sensitivities correspond to areas near the ecliptic

http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec6_3a.html
plane and represent the typical minimum depth for the All-Sky survey. The effective exposure times of the observations vary significantly with ecliptic latitude due to the survey design, increasing from twelve 7.7 s exposures at the ecliptic plane to more than a hundred near the ecliptic poles. An overview of the methodology was given in Gettings et al. (2012), and full details of the MaDCoWS galaxy cluster search method will be presented in a future paper; here, we summarize.

The search method is based on WISE All-Sky Release data, augmented by $i$-band photometry from the Sloan Digital Sky Survey (SDSS). At 3.4 $\mu$m, the apparent magnitude of an $L^*$ galaxy is only weakly dependent upon redshift at $z \gtrsim 1$ due to evolutionary and k corrections which offset the impact of increasing luminosity distance. Consequently, a magnitude-limited galaxy sample selected at 3.4 $\mu$m has a nearly uniform luminosity limit at this epoch. This is even more true for the 4.6 $\mu$m band (Eisenhardt et al. 2008), but the All-Sky WISE release is not deep enough to select at W2. In contrast, this redshift dependence increases in strength at progressively shorter wavelengths, enabling color selection of distant galaxies.

The MaDCoWS search exploits these properties using a set of magnitude and color cuts in WISE and optical bands to isolate a population of $z \gtrsim 1$ galaxies. After cleaning the WISE catalog of flagged sources and applying a 3.4 $\mu$m cut to ensure spatial uniformity in depth, we match the WISE catalog to the SDSS DR8 photometric catalog (Aihara et al. 2011). In the current version of the MaDCoWS search, which covers 15 of the 19 clusters in this paper, we then reject sources with $W1 - W2 < 0.2$ and $i < 21$, effectively removing the foreground galaxy population. The other four clusters presented here are from a preliminary search which employed the same technique but lacked the current optimization of these color and magnitude cuts. Once foreground sources are removed, we input the remaining sources to a wavelet search to identify overdensities on a scale of $\sim 3'$, which corresponds to a physical size of $\sim 1.4$ Mpc at $z \sim 1$. From the resulting wavelet-smoothed density maps we select the most-significant overdensities as MaDCoWS candidate clusters.

The remaining sources are smoothed with a Gaussian-difference wavelet kernel tuned to enhance structures on scales of $\sim 3'$, corresponding to a physical size of $\sim 1.4$ Mpc at $z \sim 1$. From these maps we identified the most statistically significant overdensities for further investigation. The centroids of the detections are used below to define the cluster center. A more detailed description of the creation of the MaDCoWS cluster catalog will be presented in a forthcoming publication (D. P. Gettings et al., in preparation).

3. FOLLOW-UP OBSERVATIONS

As described below, we have been carrying out follow-up observations to confirm WISE-selected candidate clusters. Images of the spectroscopically confirmed candidates are shown in Figure 1, and listed in Table 1. Optical imaging was obtained with the Gran Telescopio Canarias (GTC) and Gemini-North, Infrared Array Camera (IRAC; Fazio et al. 2004) imaging with the Spitzer Space Telescope, and optical spectroscopy with Keck and Gemini-North, as described below. In general, cluster candidates were chosen for optical spectroscopic confirmation based primarily on three factors: the appearance of a red sequence in the color–magnitude diagram, their visual appearance in the optical imaging, and the galaxy overdensity as measured in the IRAC images.

3.1. GTC Imaging

We obtained $i$-band imaging for five of the candidate clusters in Table 1 using the optical imaging instrument OSIRIS on the GTC in queue mode in 2012 August. A total of 18 minutes of exposure time was obtained on each of these clusters, using 6 dithered 180 s integrations. The data were processed using standard reduction procedures in IRAF and astrometrically calibrated to the USNO-B1.0 catalog (Monet et al. 2003) using SCAMP and SWarp (Bertin 2006; Bertin et al. 2002). The seeing in these optical images is approximately 0.7–0.8 arcsec. Photometric calibration of final, stacked images was performed.

Table 1

| Cluster ID   | $\alpha$ (J2000) | $\delta$ (J2000) | Imaging | Spectroscopy–Instrument: UT Dates |
|--------------|------------------|------------------|---------|----------------------------------|
| MOOa J0012+1602 | 00:12:13.0       | +16:02:16        | GMOS    | DEIMOS: 2013-09-08, 2013-09-09   |
| MOO J0024+3303  | 00:24:44.9       | +33:03:10        | GMOS    | GMOS: 2013-11-25, DEIMOS: 2013-09-09 |
| MOO J0125+1344  | 01:25:22.4       | +13:44:35        | GMOS    | GMOS: 2013-11-26, DEIMOS: 2013-09-08 |
| MOO J0130+0922  | 01:30:36.4       | +09:22:36        | GTC, IRAC | DEIMOS: 2012-10-18, 2012-10-19 |
| MOO J0133–1057  | 01:33:55.6       | −10:57:44        | GTC, IRAC | DEIMOS: 2012-10-18, 2012-10-19 |
| MOO J0212–1813  | 02:12:04.1       | −18:14:13        | GTC, IRAC | DEIMOS: 2012-10-18 |
| MOO J0224–0620  | 02:24:51.3       | −06:20:17        | GMOS    | GMOS: 2013-12-04 |
| MOO J0245+2018  | 02:45:07.9       | +20:18:15        | GMOS    | GMOS: 2013-10-16+17, DEIMOS: 2012-10-18+19 |
| MOO J0319–0025  | 03:19:25.6       | −00:25:20        | GMOS    | GMOS: 2013-09-07 |
| MOO J1155+3901  | 11:55:45.4       | +39:01:06        | GMOS    | GMOS: 2013-05-28 |
| MOO J1210+3154  | 12:10:54.3       | +31:54:40        | IRAC    | DEIMOS: 2013-05-09 |
| MOO J1319+5519  | 13:19:38.3       | +55:19:07        | GMOS    | GMOS: 2013-06-30, 2013-07-01 |
| MOO J1335+3004  | 13:35:41.7       | +30:04:13        | GMOS    | GMOS: 2013-04-19 |
| MOO J1514+1346  | 15:14:43.8       | +13:46:32        | GMOS    | GMOS: 2013-04-19, DEIMOS: 2013-07-13 |
| MOO J1625+2629  | 16:25:03.4       | +26:29:54        | IRAC    | DEIMOS: 2013-09-09 |
| MOO J2205–0917  | 22:05:37.5       | −09:17:28        | GMOS    | GMOS: 2013-10-27 |
| MOO J2320−0620  | 23:20:16.8       | −06:20:32        | GTC, IRAC | DEIMOS: 2012-10-18 |
| MOO J2348+0846  | 23:48:19.9       | +08:46:01        | GTC, IRAC | DEIMOS: 2012-10-13, 2012-10-19 |
| MOO J2355+1030  | 23:55:01.0       | +10:30:43        | GMOS    | DEIMOS: 2013-09-09 |

Notes.

a MOO stands for MaDCoWS Overdense Object.
b Source of imaging used to create color–magnitude diagrams in Figure 2.
Figure 1. (a) MOO 0012+1602, z = 0.94, left: 3' × 3' WISE W1 image. The white circles represent sources identified as probable high-redshift galaxies based upon color and magnitude cuts (see text). The white circles have a diameter of 8.1′, similar to the FWHM of the WISE W1 and W2 Atlas images. North is up and east left for all images. Right: 3' × 3' z-band image of the same area as in the left panel. Red circles mark the spectroscopically confirmed members (some of which lie outside the FOV of the image) and the yellow boxes mark the objects in the red sequence (see text). (b) MOO 0024+3303, z = 1.11, as above; W1 image on the left, z-band image on the right. (c) MOO 0125+1344, z = 1.12, as above; W1 image on the left, z-band image on the right. (d) MOO 0130+0922, z = 1.15, as above; W1 image on the left, i-band image on the right. (e) MOO 0133+1057, z = 0.96, as above; W1 image on the left, i-band image on the right. (f) MOO 0212−1813, z = 1.09, as above; W1 image on the left, i-band image on the right. (g) MOO 0224−0620, z = 0.81, as above; W1 image on the left, z-band image on the right. (h) MOO 0245+2018, z = 0.76, as above; W1 image on the left, i-band image on the right. (i) MOO 0319−0025, z = 1.19, as above; W1 image on the left, z-band image on the right. (j) MOO 1155+3901, z = 1.01, as above; W1 image on the left, z-band image on the right. (k) MOO 1210+3154, z = 1.05, as above; W1 image on the left, 3.6μm-band image on the right. (l) MOO 1319+5519, z = 0.94, as above; W1 image on the left, z-band image on the right. (m) MOO 1335+3004, z = 0.98, as above; W1 image on the left, z-band image on the right. (n) MOO 1514+1346, z = 1.06, as above; W1 image on the left, z-band image on the right. (o) MOO 1625+2629, z = 1.20, as above; W1 image on the left, 3.6μm-band image on the right. (p) MOO 2205−0917, z = 0.93, as above; W1 image on the left, z-band image on the right. (q) MOO 2320−0620, z = 0.92, as above; W1 image on the left, i-band image on the right. (r) MOO 2348+0846, z = 0.89, as above; W1 image on the left, i-band image on the right. (s) MOO 2355+1030, z = 1.27, as above; W1 image on the left, z-band image on the right.

(A color version of this figure is available in the online journal.)
using DR10 (Ahn et al. 2014) photometry of SDSS stars in each field.

3.2. Gemini-North Imaging

As part of a queue program at Gemini-North (PI: Brodwin) which includes spectroscopy, we obtained GMOS $r$- and $z$-band imaging in the 2013A and 2013B semesters on 12 of the candidates listed in Table 1. A series of dithered exposures was obtained in each band, $5 \times 180$ s in the $r$ band, and $12 \times 80$ s in the $z$ band. The data were processed using standard reduction procedures in IRAF and astrometrically calibrated to the USNO-B1.0 catalog (Monet et al. 2003) using SCAMP and SWarp. The seeing in the GMOS images is typically 0.6 arcsec. Photometric calibration was obtained using DR10 photometry of SDSS stars that appear in each field.
3.3. IRAC Imaging

As part of a larger Spitzer survey of MaDCoWS candidates (PI: Gonzalez), we obtained IRAC 3.6 and 4.5 μm imaging in Cycle 9 for 200 MaDCoWS cluster candidates including all of the clusters in Table 1; here, we make use of the IRAC data for only seven of the candidates listed in Table 1 in the cases where our optical imaging is either incomplete or nonexistent. A series of six dithered 30 s exposures was obtained with IRAC in each channel for a total exposure time of 180 s. The basic calibrated data were reduced and mosaiced using MOPEX (Makovoz & Khan 2005) and resampled to a pixel scale of 0.6 arcsec. The PSF in the IRAC images has a FWHM ~1.7 arcsec. A more detailed presentation of the MaDCoWS IRAC program will be made in a future publication.

3.4. Keck Spectroscopy

The optical/infrared catalogs described below in Section 4.1 were used to design slit-masks for use with DEIMOS at the
W. M. Keck Observatory to obtain redshifts of potential cluster galaxies. For clusters where Gemini $r - z$ photometry was available, we used the red sequence as primary targets, whereas for clusters with GTC imaging, we used $i - W1$ colors to select targets, and for the clusters with only Spitzer imaging, we selected on the basis of [3.6]–[4.5] color. The general approach to designing the slit masks was to rely on the red sequence as the source of the highest priority objects, weighting by cluster-centric radius, and then filling in the masks with other galaxies at larger radii selected by WISE W1–W2 color. The slitlets in the masks had widths of 1′′1 and minimum lengths of 5 arcsec. Spectra were obtained using the 600 line grating and the GG495 filter on three observing runs in the 2012B, 2013A, and 2013B semesters, when conditions were generally clear with seeing of 0′′6–1′′0. Table 1 lists the observation dates for each cluster. For most masks we obtained three 1200 s exposures, with longer exposure times being devoted to the higher redshift candidates. The DEIMOS spectra were reduced using the DEEP2 pipeline.
The relative spectral response of the extracted spectra was calibrated via observations of Feige 34 and BD 28+4211.

3.5. Gemini-North Spectroscopy

Using the optical catalogs created from GMOS preimaging, we designed slit masks for GMOS to obtain redshifts of potential cluster galaxies, following a similar procedure to design masks. Spectra were obtained using 1′0 slit widths, the R400 grating, and the RG810 filter. Three sets of nod and shuffle sequences were obtained at each of two central wavelength settings (8100 and 8200 Å). Each nod and shuffle sequence used ±0.75 arcsec nods, with 9 cycles of 60 s exposures, so the total on-source exposure time was 6480 s. The seeing was in the 0′.6–1′ range. Table 1 lists the observation dates for each cluster. The GMOS spectra were reduced using standard procedures in IRAF.
4. RESULTS

4.1. Color–Magnitude Diagrams

For all of the imaging described above, SExtractor (Bertin & Arnouts 1996) catalogs were generated using the longer wavelength image for detection. Photometry was obtained from the shorter wavelength image using SExtractor in dual-band mode. Magnitudes were measured using circular apertures with a diameter of 2.5 arcsec, except for the clusters where we use IRAC images for which the aperture size is 4 arcsec diameter, and were aperture-corrected. All magnitudes are on the AB system.

Color–magnitude diagrams (CMDs) were constructed for all the confirmed clusters in Table 1 and are presented in Figure 2. For MOO 1625+2629 and MOO 1210+3154 we do not have any optical imaging, so the CMDs use [3.6] − [4.5] colors, which...
Figure 1. (Continued)

The spectroscopic campaigns, as both the spectroscopic results and IRAC imaging were used to refine the cluster search. To assess the 4.2. Redshifts

Redshifts of objects in each cluster were determined by visual inspection of the reduced spectra and identification of prominent spectral features including the 4000 Å break, the Ca H+K absorption lines, and the [O ii] λ3727 emission line. Sample spectra are shown in Figure 3 for one of the lower-redshift clusters and for one of the higher redshift clusters. Redshift information for all the cluster members is given in Table 2. The spectroscopic member galaxies are marked in the color–magnitude diagrams as well as in the optical/infrared images shown in Figures 1 and 2, respectively. Clusters for which at least five objects have redshifts within ±2000(1 + z) km s⁻¹ and within a radius of 2 Mpc are considered to be confirmed.

The overall results of the spectroscopy are summarized in Table 3, which lists the confirmed clusters with their mean redshifts, and in Figure 4. The redshift histogram shows that the MaDCoWS selection technique effectively identifies z ~ 1 galaxy clusters. Four of the new clusters, represented in Figure 4 imaging were used to refine the cluster search. To assess the purity of the MaDCoWS sample, we consider the confirmation rate of cluster candidates that are among the 200 highest significance detections in the current iteration of the WISE search. From this list, we have spectroscopically confirmed 14 clusters. In addition to these, we obtained optical spectroscopy of 6 other candidates in the current MaDCoWS selection. For one candidate the redshifts show the presence of multiple groups

| Objecta | α (J2000) | δ (J2000) | zQ Type |
|---------|-----------|-----------|---------|
| MOO0012+1602.1275 | 00:12:13.699 | 16:02:04.7 | 0.946 B E |
| MOO0012+1602.494 | 00:12:18.742 | 16:02:46.0 | 0.946 A A |
| MOO0012+1602.1775 | 00:12:11.249 | 16:01:51.3 | 0.940 B A |
| MOO0012+1602.1776 | 00:12:09.983 | 16:02:16.4 | 0.950 A A |
| MOO0012+1602.1783 | 00:12:08.601 | 16:02:38.2 | 0.949 B A |
| MOO0012+1602.825 | 00:12:14.799 | 16:02:31.6 | 0.938 A E |
| MOO0012+1602.599 | 00:12:18.732 | 16:02:19.1 | 0.941 B A |
| MOO0012+1602.1950 | 00:12:10.457 | 16:02:14.4 | 0.950 B A |
| MOO0012+1602.1580 | 00:12:06.854 | 16:02:17.2 | 0.952 B A |
| MOO0012+1602.672 | 00:12:17.166 | 16:02:27.6 | 0.943 A A |
| MOO0012+1602.912 | 00:12:14.223 | 16:02:20.5 | 0.941 A E |
| MOO0012+1602.688 | 00:12:16.302 | 16:02:41.2 | 0.938 A E |
| MOO0012+1602.371 | 00:12:18.799 | 16:03:14.7 | 0.932 A E |
| MOO0012+1602.941 | 00:12:13.415 | 16:02:34.1 | 0.952 B A |
| MOO0012+1602.755 | 00:12:16.104 | 16:02:29.3 | 0.952 A A |
| MOO0012+1602.15574 | 00:12:23.627 | 15:57:49.7 | 0.948 A E |
| MOO0012+1602.15580 | 00:12:29.705 | 15:58:02.4 | 0.947 A E |
| MOO0012+1602.760 | 00:12:15.437 | 16:02:36.8 | 0.942 A E |
| MOO0012+1602.1933 | 00:12:13.403 | 16:01:55.7 | 0.940 B A |
| MOO0012+1602.531 | 00:12:22.798 | 16:01:26.1 | 0.930 B A |
| MOO0012+1602.666 | 00:12:14.695 | 16:00:33.7 | 0.948 A A |
| MOO0012+1602.884 | 00:12:14.418 | 16:02:29.1 | 0.942 B A |
| MOO0012+1602.2053 | 00:12:15.516 | 16:01:50.0 | 0.944 B A |

Notes. Redshifts of individual galaxies. This is a partial listing of the member galaxies in only one cluster; redshifts of individual galaxies for all the clusters will be available electronically. The Q column describes the quality of the redshift using the following codes: A = high degree of certainty based on multiple features; B = reasonable certainty based on at least two features. In the Type column, E means the optical spectrum has an emission line (nearly always [O ii] λ3727), and A means it is an absorption line (Ca H+K, D4000) spectrum.

* The object ID is created from the cluster MOO ID followed by the R.A. and Decl. of the object.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 2. Color–magnitude diagrams covering a circular area with a diameter of 3 arcmin (~1.4 Mpc). Uncertainties of one σ in the colors are shown. The color and magnitude of an L* model galaxy (described in the text) at the cluster redshift are represented by the horizontal and vertical dashed lines. Spectroscopic members are marked by red circles; members outside the 3 arcmin diameter area are represented by only a red circle. Some members lie outside of the follow-up imaging area and are not shown in the CMD.

(A color version of this figure is available in the online journal.)
along the line of sight and so we deem this candidate to be a failure. For the remaining five candidates, we find a spread of redshifts with no definitive evidence of groups or clusters. Because only one mask was obtained on each of these five candidates, we cannot yet confidently state whether they are real or spurious. Considering the limiting cases where all or none of these five candidates are spurious, we find that the purity lies in the range 70%–95%.
5. DISCUSSION

We have presented imaging and spectroscopy that confirms 19 new galaxy clusters in the $0.7 < z < 1.3$ range, which were selected using the All-Sky WISE data release. This set of new clusters, which includes nine at $z > 1$, robustly demonstrates the viability of conducting an all-sky search for such objects using WISE. The distribution of the cluster redshifts indicates that our final MaDCoWS selection technique identifies galaxy clusters primarily in the $0.8 < z < 1.3$ range. To date, five
of the clusters in Table 3 have been observed by CARMA and have measured SZ decrements, consistent with $M_{200}$ in the range $2-6 \times 10^{14} M_{\odot}$ range (M. Brodwin et al., in preparation). As a result, the clusters identified by MaDCoWS are expected to form a valuable sample for obtaining cosmological constraints, and for better understanding of the formation of massive clusters and their constituent galaxy populations at $z > 1$.

The color–magnitude diagrams, optical images, and spectroscopy suggest that the MaDCoWS clusters span a variety of cluster types. Some clusters such as MOO 1514+1316 appear to be relaxed, with a centrally concentrated core of galaxies, a well-defined red sequence, and few emission-line objects.
However, other clusters span the range of possible combinations of these characteristics, some having few emission-line objects but little if any spatial concentration in a core region, and others having a relatively high fraction of emission-line galaxies and a well-formed cluster core. The optical spectroscopy was being carried out while we were fine-tuning the WISE selection procedure, and this could contribute to the variety of cluster properties in the confirmed clusters. As the number of confirmed clusters and members in each cluster increases, it will become possible to draw more robust conclusions about the galaxy populations in MaDCoWS clusters.

The prospects for extending the redshift reach, the upper mass range, and the effective area of MaDCoWS are excellent. Some of the newly confirmed clusters were chosen for follow-up without the benefit of seeing the IRAC images, which were obtained later than the observing runs at the ground-based telescopes. Now that we can fully exploit our IRAC imaging of the 200 richest WISE cluster candidates to select targets for future follow-up at, e.g., CARMA and Keck, we expect that the mean cluster mass of the MaDCoWS cluster sample will rise. Additionally, the clusters presented here were discovered using the original All-Sky WISE data. The AllWISE data release, which contains twice the exposure time in the W1 and W2 bands, now provides deeper photometry in the W1 and W2 bandpasses, enabling a search extending to higher redshifts which we are now undertaking. In the future, the prospect of combining the one year of AllWISE survey data with the three years of additional survey data expected from the recently reactivated NEOWISE survey (Mainzer et al., in preparation) should allow us to select at W2 and identify robust cluster candidates to $z > 1.5$.

Finally, the area so far covered by MaDCoWS has been restricted to that of the SDSS, as their optical imaging efficiently suppresses low-redshift interlopers that would otherwise be selected by the WISE W1–W2 color. As more area is covered by optical imaging surveys of similar quality, such as the Dark Energy Survey, we will expand the area of our WISE search for the most massive galaxy clusters at $z \sim 1$ and above.

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