Radio Selection of the Most Distant Galaxy Clusters


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E. Daddi1, S. Jin1,2, V. Strazzullo3, M. T. Sargent4, C. Tang1,5, C. Ferrara6, E. Schinnerer7, V. Smolčič8, A. Calabrò9, R. Coogan1,4, J. Delhaize8, I. Delvecchio8, D. Elbaz1, R. Gobat7, Q. Gu2, D. Liu7, M. Novak8, and F. Valentino10

1 CEA, IRFU, DAP, AIM, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, CNRS, F-91191 Gif-sur-Yvette, France
2 School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China
3 Department of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, D-81679 Munich, Germany
4 Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK
5 Institute of Astronomy, the University of Tokyo, and National Observatory Of Japan, Osawa, Mitaka, Tokyo 181-0015, Japan
6 Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Bd de l’Observatoire, CS 34229, F-06304 Nice cedex 4, France
7 Max Planck Institute for Astronomy, Konigstuhl 17, D-69117 Heidelberg, Germany
8 Department of Physics, Faculty of Science, University of Zagreb, Bijenička cesta 32, Zagreb 10000, Croatia
9 School of Physics, Korea Institute for Advanced Study, Hoegiro 85, Dongdaemun-gu, Seoul 02455, Korea
10 Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark

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Abstract

We show that the most distant X-ray-detected cluster known to date, Cl J1001 at $z_{\text{spec}} = 2.506$, hosts a strong overdensity of radio sources. Six of them are individually detected (within $10''$) in deep $0''75$ resolution VLA 3 GHz imaging, with $S_{1\text{GHz}} > 8 \mu$Jy. Of the six, an active galactic nucleus (AGN) likely affects the radio emission in two galaxies, while star formation is the dominant source powering the remaining four. We searched for cluster candidates over the full COSMOS 2 deg$^2$ field using radio-detected 3 GHz sources and looking for peaks in $\Sigma^{5}$ density maps. Cl J1001 is the strongest overdensity by far with $>10\sigma$, with a simple $\Sigma^{5}_{\text{pre}} > 1.5$ preselection. A crude photometric rejection of $z < 1$ radio foregrounds leaves Cl J1001 as the second strongest overdensity, while even using all radio sources Cl J1001 remains among the four strongest projected overdensities. We conclude that there are great prospects for future deep and wide-area radio surveys to discover large samples of the first generation of forming galaxy clusters. In these remarkable structures, widespread star formation and AGN activity of massive galaxy cluster members, residing within the inner cluster core, will ultimately lead to radio continuum as one of the most effective means for their identification, with detection rates expected in the ballpark of 0.1–1 per square degree at $z \geq 2.5$. Samples of hundreds such high-redshift clusters could potentially constrain cosmological parameters and test cluster and galaxy formation models.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – galaxies: high-redshift – radio continuum: galaxies

1. Introduction

The identification of the most distant, $z \geq 2$ galaxy clusters —i.e., structures consistent with a single massive dark matter halo as opposed to megaparsec-scale loose overdensities like protoclusters (Diener et al. 2015)—is a very active topic of current research (see Overzier 2016 for a recent review). They represent the earliest generation of massive collapsed structures, progenitors to Coma-like clusters, and their abundance can constrain cosmological parameters. Also, they are unambiguous formation sites of massive ellipticals, and hence hold promise to shed light on the elusive processes that lead to the formation of passive, early-type galaxies. It is currently unclear if the morphological transformation of galaxies into spheroidal systems happens before or after entering the densest early cluster cores. The same holds for the quenching of star formation and passivization. High-redshift clusters are also interesting laboratories for studying (Valentino et al. 2016) the interaction between star formation/active galactic nucleus (AGN) activity and the hot intracluster medium (ICM), energy injection into the ICM, and its thermodynamical evolution. At redshifts $z \sim 1.5–3$ theory predicts that massive $\sim 10^{13–14} M_{\odot}$ dark matter halos should undergo a transition from being fed by cold streams to being shielded by a hot atmosphere that prevents refueling with fresh gas (Dekel et al. 2009). This process is not well constrained by theory. Observations are needed to trace the redshift and duration of this transition. Evidence of persistent activity in massive structures at $z \sim 2–2.5$ suggests that this might occur later and/or at higher masses than currently expected (Valentino et al. 2015, 2016; Overzier 2016; Wang et al. 2016). Statistics from a larger number of clusters are required for definitive conclusions. Surveys aiming at detecting hot ICM, via X-rays or Sunyaev–Zeldovich (SZ) emission, generally lack sensitivity for identifying clusters beyond $z \sim 2$. Clusters found approaching such a limit are so massive ($\gtrsim 10^{15} M_{\odot}$; Stanford et al. 2012; Newman et al. 2014) and evolved (i.e., dead) that they are far less interesting for the science discussed above. More typical $z \geq 2$ systems have been discovered looking for concentrations of massive galaxies (e.g., Gobat et al. 2011, 2013; Yuan et al. 2014; Strazzullo et al. 2015; Wang et al. 2016), and X-ray emission searched for at their known positions, a posteriori.

Quite strikingly, the most distant X-ray-detected cluster known to date at $z = 2.506$ (Wang et al. 2016, hereafter W16) displays a startling amount of star formation in its core ($L_{IR} \sim 10^{10} L_{\odot}$). Searching for concentrations of galaxy activity from star formation or AGNs might thus be a competitive means for finding the most distant structures. In this Letter, we explore this idea analyzing the W16 cluster radio continuum properties, keeping in mind that forthcoming deep radio surveys will cover large sky areas to remarkable depths. We use standard cosmology ($70, 0.3, 0.7$) and a Chabrier IMF.
2. Radio Continuum Emission from Galaxies in a z = 2.5 Cluster

Deep VLA observations of the COSMOS field at 3 GHz have been obtained, fully reduced, analyzed, and publicly released by Smolčić et al. (2017). We have used the point-spread function (PSF) fitting technique and cataloging method of Liu et al. (2017) to obtain radio flux density measurements at 3 GHz for all Ks-selected galaxies in the COSMOS2015 catalog of Laigle et al. (2016), supplemented with sources from Muzzin et al. (2013). Full details of this radio catalog together with the multi-wavelength properties in Herschel, Spitzer, SCUBA2, and other submillimeter probes of COSMOS galaxies will be presented in a forthcoming publication (S. Jin et al. 2017, in preparation). We concentrate here on the radio properties of galaxies in the surroundings of the W16 cluster, as compared to those in the full COSMOS 2 deg$^2$ field. Thanks to our PSF fitting technique we can push to deeper radio flux levels compared to blindly extracted signal-to-noise ratio (S/N) > 5 catalogs in Smolčić et al. (2017), with high fidelity and completeness and with a very low expected spurious detection rate. Our simulations return typical rms sensitivities of 2.5–2.7 $\mu$Jy with well-behaved Gaussian-like uncertainties, close to the expected 2.3 $\mu$Jy noise, allowing for reliable S/N > 3 detections at 3 GHz down to about 8 $\mu$Jy. Radio sources without a Ks counterpart would be lost by our technique and are added back to the sample from the Smolčić et al. catalog (sources with multiple cataloged components, e.g., radio lobes, had been combined into one catalog entry).

Fitting a total of 589,713 priors, we obtain 17,803 radio continuum detections with S/N > 3 in the COSMOS field, extracted over an area of 1.7 deg$^2$ from our Ks-band priors (doubling the number of detections at a fixed area, compared to the blind catalog). We find that six galaxies are radio detected within a 10$''$ radius from the center$^{11}$ of the W16 cluster; see Figure 1 and Table 1. These are all spectroscopically confirmed cluster members and very red galaxies. The faintest, two MS galaxies, are not present in the Smolčić catalog. Four of the radio detections exhibit radio flux densities consistent with the FIR–radio correlation for star-forming galaxies at their redshift (Yun et al. 2001; Delhaize et al. 2017). Their radio emission is naturally explained by star formation alone. Two of these are relatively low mass while hosting high star formation rates (SFRs), i.e., they are starburst-like galaxies, probably merger-driven. The other two are consistent with the main sequence at $z = 2.5$ (see also W16). The remaining two detections have a radio flux excess over the SFRs inferred from the Atacama Large Millimeter/submillimeter Array (ALMA; Table 1; W16) by factors of $\geq 3$–5 and do likely contain radio AGNs, with moderate intrinsic luminosities $\lesssim 10^{25}$ W Hz$^{-1}$ (at rest 1.4 GHz, using also 1.4 GHz data; Schinnerer et al. 2010). These two radio AGNs do not exhibit any signatures of mid-IR or X-ray AGN activity (e.g., Delvecchio et al. 2017). The median ALMA 850 $\mu$m to radio 3 GHz flux ratio is $\sim 150$ (Table 1).

The total radio flux of the six cluster detections is 130 $\mu$Jy with PSF fitting, or a maximum of 170 $\mu$Jy when accounting for the possibly extended nature of some sources. Depending on the exact value, which radio–IR correlation we adopt, and factoring in possible AGN components, this corresponds to 20%–90% of the expectation from their Herschel-ALMA luminosities (W16). We radio-detect all sources producing the bulk of the SFR activity, with tentative evidence of a lower radio/L$_{IR}$ ratio compared to the field.

Figure 2 shows distributions of photometric redshift, Ks-band magnitudes, and radio fluxes. Based on Kolmogorov–Smirnov tests, the $z = 2.5$ cluster galaxies are significantly fainter in Ks and at higher redshift than most radio detections above 8 $\mu$Jy at 3 GHz. Instead, their radio flux density distribution, spanning 8–40 $\mu$Jy (see Table 1), is still consistent with a random sampling of the parent catalog.

3. Radio Selection of the z = 2.5 W16 Cluster

The six detections single out the W16 cluster as a very special environment in the radio, enough to allow its preselection as a cluster candidate even based on radio information alone. Such a selection can reach even stronger confidence when some low-level ancillary information is used in addition to radio, such as could be expected to be available in support of future generation, wide-area radio surveys. Following Figure 2, we considered the case of near-IR Ks-band imaging being available, or some moderate-quality photometric redshifts distinguishing $z > 1.5$ sources, like the case for example with the BzK color preselection (Daddi et al. 2004) or red color selections (Franx et al. 2003; see also W16) or IRAC/WISE red colors (e.g., Papovich et al. 2010). Finally, we also considered the direct use of COSMOS-quality photometric redshifts with an accuracy of about 7% in $(1 + z)$ at $z \sim 2$–3 as available for W16 cluster galaxies.

As a first step, we compute the Poisson probabilities for chance associations of six galaxies within a 10$''$ radius. This approach is approximative, given that the size and radius of the

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$^{11}$ Average position of the six radio sources.
Table 1

Radio Detections in the W16 Cluster

<table>
<thead>
<tr>
<th>ID-Jin</th>
<th>ID-COSMOS2015 or Muzzin</th>
<th>R.A. deg</th>
<th>Decl. deg</th>
<th>Distance Mpc</th>
<th>z_phot</th>
<th>z_spec</th>
<th>log ( M^* ) ( M_\odot )</th>
<th>S1.4GHz ( \mu )Jy</th>
<th>S850 ( m )Jy</th>
<th>Ks AB mag</th>
<th>Origin of Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>681633</td>
<td>130651</td>
<td>150.2389798</td>
<td>2.3339305</td>
<td>8.5</td>
<td>2.69</td>
<td>2.50 ± 0.02</td>
<td>11.18</td>
<td>27.6 ± 2.7</td>
<td>&lt;1.2 (3σ)</td>
<td>22.43</td>
<td>AGN</td>
</tr>
<tr>
<td>683281</td>
<td>130891</td>
<td>150.2398843</td>
<td>2.3364591</td>
<td>4.9</td>
<td>2.74</td>
<td>2.513</td>
<td>11.33</td>
<td>20.6 ± 2.5</td>
<td>3.77 ± 0.32</td>
<td>22.56</td>
<td>SB</td>
</tr>
<tr>
<td>683795</td>
<td>130933</td>
<td>150.2387007</td>
<td>2.3368268</td>
<td>2.2</td>
<td>2.29</td>
<td>2.500</td>
<td>11.02</td>
<td>24.1 ± 2.7</td>
<td>1.66 ± 0.21</td>
<td>22.31</td>
<td>AGN</td>
</tr>
<tr>
<td>684410</td>
<td>130901</td>
<td>150.2392700</td>
<td>2.3363813</td>
<td>2.7</td>
<td>2.36</td>
<td>2.508</td>
<td>11.23</td>
<td>8.8 ± 2.9</td>
<td>2.23 ± 0.41</td>
<td>21.7</td>
<td>MS</td>
</tr>
<tr>
<td>684496</td>
<td>130949</td>
<td>150.2370141</td>
<td>2.3357152</td>
<td>5.8</td>
<td>2.26</td>
<td>2.503</td>
<td>11.32</td>
<td>10.8 ± 3.2</td>
<td>1.69 ± 0.25</td>
<td>20.93</td>
<td>MS</td>
</tr>
<tr>
<td>10131077</td>
<td>131077</td>
<td>150.2373500</td>
<td>2.3381379</td>
<td>8.0</td>
<td>2.82</td>
<td>2.494</td>
<td>10.92</td>
<td>39.5 ± 3.1</td>
<td>5.26 ± 0.26</td>
<td>24</td>
<td>SB</td>
</tr>
</tbody>
</table>

Note. The photometric redshifts, coordinates, and Ks magnitudes are from the COSMOS2015 catalog (Laigle et al. 2016), except ID-10131077 (Muzzin et al. 2013), with Ks measured at the radio position. Spectroscopic redshifts are from W16. Radio measurements and relative IDs are from the S. Jin et al. (2017, in preparation) catalog. Distances are relative to the cluster center, which is located at [150.2385331, 2.3362418]. For the “Origin of Radio” column see the discussion in the text.
search area were chosen ad hoc, although we note that the \(10''\) radius corresponds to the core radius of a massive \(\sim 10^{14}\) \(M_\odot\) cluster at \(z > 2\) (W16). More importantly, this approach neglects clustering, i.e., the presence of galaxies in smaller structures, filaments, and even projected random association of physical galaxy pairs, that can conspire to increase the spurious (non-single cluster) occurrence of a large counting event. This can nevertheless provide a useful starting guide. The Poisson probability of a W16-like association is fairly low even when just considering radio sources: 0.02 events are expected in COSMOS. This decreases to \(\sim 2.0 \times 10^{-4}\) considering only Ks-faint radio sources, and to \(10^{-5}\) and \(10^{-7}\) for sources with \(z_{\text{phot}} > 1.5\) and \(2 < z_{\text{phot}} < 3\), respectively.

A more objective approach is to use the \(\Sigma_5\) peak statistics\(^{12}\) to search for overdensities in the full COSMOS field, following the method from Strazzullo et al. (2015), which allows for a derivation of the dispersion and thus for an evaluation of their significance. Figure 3 shows the resulting \(\Sigma_5\) maps and distribution of \(\Sigma_5\) readings over the full COSMOS areas for the various selections described in Table 2. When allowing for a photometric redshift preselection of high-redshift radio sources, the W16 cluster is recovered as the first ranked overdensity. Pre-selecting radio sources with \(2 < z < 3\), the W16 cluster is a \(12.3\sigma\) overdensity, long ahead of the second ranking object, seen with \(6.5\sigma\) at position [149.86924, 2.3417165]. With a cruder \(z_{\text{phot}} > 1.5\) constraint, as obtainable from color selections, the W16 cluster is detected at \(>10\sigma\). The second ranking cluster is again detected with far less significance at \(7.6\sigma\) near [150.31505, 2.7126151], This latter structure seems loose and possibly the result of line-of-sight alignments. Using all Ks-faint radio sources returns the W16 cluster as the second ranking overdensity with \(8.7\sigma\), after a \(7.8\sigma\)–\(8.1\sigma\) peak near [150.14933, 2.5922460] (however, the latter is likely a chance alignment including low-z sources), when using all radio-detected sources with \(S/N > 3\) the W16 is found as the fourth ranked \(7.7\sigma\), after three more \(7.8\)–\(8.1\sigma\) peaks [150.14933, 2.5922460]–[150.00879, 2.2741797]–[149.83185, 2.5704069]. All of the latter appear to be chance alignments, judging from their \(z_{\text{phot}}\), except perhaps a possibly genuine but loose concentration at \(z \sim 0.9\) in the latter case. A detailed discussion of the nature of these possibly significant \(\Sigma_5\) peaks is beyond the scope of this Letter, where we concentrate on the well-studied case of the spectroscopically confirmed \(z = 2.506\) cluster W16.

We caution that with six sources only and with two close to the limit of our current radio photometry, the W16 cluster provides a highly significant but perhaps fragile detection. One could imagine that out of many realizations of a similar dark matter halo structure at \(z = 2.5\), at times, one or two galaxies could remain below current detection limits (for effects of noise, lower SFR, lower AGN activity), preventing detection in...
the radio in presence of low number statistics. Those four of the six W16 radio detections that appear in the Smolčić et al. 3 GHz catalog (i.e., have $S_{3\,\text{GHz}} > 20\ \mu\text{Jy}$) still define an $\sim 11\sigma$ overdensity (when adopting, ad hoc, the $\Sigma_4$ statistics).

4. Discussion

We have demonstrated above that using only radio-detected sources, ideally with alternative information in the form of photometric redshifts or even single-band photometry, allows
us to pinpoint the W16 cluster. This is quite promising news for future large area radio surveys, which will reach very faint flux densities (Padovani 2016). For example, even in phase1, SKA will likely carry out a full-sky survey to few μJy sensitivity and with ~2σ resolution at 1–2 GHz, while covering ~1000 deg² to ~1 μJy depth and subarcsec resolution (Prandoni & Seymour 2015), surpassing the depth and sensitivity of our 3 GHz VLA data, allowing us in principle to find W16-like clusters over the whole sky, and perhaps much further away and in great numbers. Current plans also envisage excellent prospects for ngVLA, when observing at ~2–3 GHz (Selina & Murphy 2017). Our work identifies important synergies between future radio, optical, NIR, and X-ray surveys. The community preparing future multiband facilities is perfectly aware of the necessity of this joint effort, which therefore starts the interplay between ICM and galaxy formation activity, especially be used to pin down massive star-forming galaxies. But even more crucially, the variety of the best-fitting Γ distribution. The variance is in all cases ~0.04 in the log, while the field average moves from 10² deg⁻² for the full radio sample to 10⁵ deg⁻² for the 2 < zphot < 3 case (see also Figure 3, the average separation changing by a factor of 3 as a result of the changing number density).

<table>
<thead>
<tr>
<th>Selection</th>
<th>Full sample</th>
<th># in R = 10⁶(1)</th>
<th>P(≥6)(2)</th>
<th>Det. Rate(3)</th>
<th>Σ_\nu Peak Rank</th>
<th>Comments(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N_{16} &gt; 3</td>
<td>17803</td>
<td>0.25</td>
<td>3.0 × 10⁻⁷</td>
<td>0.02</td>
<td>4</td>
<td>7.6σ, after 3 with 7.8–8.1σ</td>
</tr>
<tr>
<td>S/N_{16} &gt; 3 &amp; Ks &gt; 20.5</td>
<td>8016</td>
<td>0.11</td>
<td>2.8 × 10⁻⁹</td>
<td>2.0 × 10⁻⁴</td>
<td>2</td>
<td>8.7σ, after a 9.2σ</td>
</tr>
<tr>
<td>S/N_{16} &gt; 3 &amp; z_{phot} &gt; 1.5</td>
<td>4952</td>
<td>0.07</td>
<td>1.6 × 10⁻¹⁰</td>
<td>10⁻⁴</td>
<td>1</td>
<td>10.0σ, the second is at 7.6σ</td>
</tr>
<tr>
<td>S/N_{16} &gt; 3 &amp; 2 &lt; z_{phot} &lt; 3</td>
<td>1994</td>
<td>0.03</td>
<td>1.4 × 10⁻¹²</td>
<td>10⁻⁷</td>
<td>1</td>
<td>12.3σ, the second is at 6.5σ</td>
</tr>
</tbody>
</table>

Note. (1) Assumes a 1.7 deg² area of the Laigle Ultra-VISTA catalog. (2) Poisson probability. (3) Number of expected chance associations of ≥6 objects within 10⁶ in the full COSMOS field, neglecting clustering effects, after considering there are 70,000 independent realizations of 10⁶ radio fields, in COSMOS. (4) The significance (in σ) is computed with respect to the peak value of the distribution of log(Σ_ν) readings over the whole field. The σ is defined as the squared root of the variance of the best-fitting Γ distribution. The variance is in all cases ~0.04 in the log, while the field average moves from 10² deg⁻² for the full radio sample to 10⁵ deg⁻² for the 2 < z_{phot} < 3 case (see also Figure 3, the average separation changing by a factor of 3 as a result of the changing number density).

The W16 cluster recovery performance obtainable from radio samples is quite comparable to that achievable using J − Ks color on Ks-selected samples that returned 11.6σ (W16), with respect to 12.3σ here, both first rank. The two techniques are complementary and could beneficially be used together: the advantage of the radio is that it is insensitive to dust obscuration and directly selects on the galaxy star formation activity (and AGN emission adds on top of that), thus pinpointing forming/active clusters, while a pure selection on optical colors could potentially reveal old and dead clusters as well. This approach is also quite different from the use of very luminous radio-galaxies as massive beacons to locate distant clusters (e.g., Miley et al. 2006; Miley & De Breuck 2008; Galametz et al. 2012; Cooke et al. 2015), but future large area radio surveys might combine the
two efforts, allowing one to select at the same time the rare ultra-bright radio-galaxies as well as the faint cluster galaxies, thus clarifying the cosmic relevance of (proto)clusters around radio-galaxies. While subject to similar limitations as Herschel searches, Planck Collaboration XXXVII (2015) and Planck Collaboration XXXIX (2016) selected large samples of high-redshift protocluster candidates. However, these candidates likely mostly comprise chance alignments of smaller structures at different redshifts (Negrello et al. 2017).

Based on the recovery of a single W16-like cluster in the COSMOS field, we expect a return of 0.1–1 deg$^{-2}$ W16-like clusters at the 68% confidence level (Poisson counts). Even limiting the SKA1 survey to over 1000 deg$^2$ could thus produce between 100–1000 $z \gtrsim 2.5$ clusters. The number density of similarly massive halos at $z > 3.5$ would be about $\times 10$ smaller, still allowing sizable samples of up to 10–100. At $z = 3.5$ we would expect $\times 2$ smaller radio fluxes compared to $z = 2.5$ at fixed observing frequency and luminosity. This could be mitigated by the expected increase of the specific SFR with redshift, and the SKA1 will reach deeper than our current data.

As discussed in W16, the identification of this structure in a field like COSMOS is somewhat in tension with ΛCDM, suggesting that actual returns will be toward the lower range, or the mass of the W16 system has been overestimated. However, expected numbers are large enough that future samples of high-redshift clusters might allow interesting tests of cosmology, in addition to cluster and galaxy formation physics, given that Athena will have the sensitivity to constrain their dark matter halo masses from the X-rays (e.g., Padovani et al. 2017).

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**ORCID iDs**

E. Daddi @ https://orcid.org/0000-0002-3331-9590  
V. Strazzullo @ https://orcid.org/0000-0001-7975-2894  
M. T. Sargent @ https://orcid.org/0000-0003-1033-9684  
E. Schinnerer @ https://orcid.org/0000-0002-3933-7677  
R. Gobat @ https://orcid.org/0000-0003-0121-6113

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