SPECTROSCOPIC CONFIRMATION OF A COMA CLUSTER PROGENITOR AT $z \sim 2.2$

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ABSTRACT

We report the spectroscopic confirmation of a new protocluster in the COSMOS field at $z \sim 2.2$, COSMOS Cluster 2.2 (CC2.2), originally identified as an overdensity of narrow-band selected Hα emitting candidates. With only two masks of Keck/MOSFIRE near-IR spectroscopy in both $H$ ($\sim 1.47$-$1.81$ μm) and $K$ ($\sim 1.92$-$2.40$ μm) bands ($\sim 1.5$ hour each), we confirm 35 unique protocluster members with at least two emission lines detected with S/N > 3. Combined with 12 extra members from the zCOSMOS-deep spectroscopic survey (47 in total), we estimate a mean redshift and a line-of-sight velocity dispersion of $z_{\text{mean}}=2.25224 \pm 0.00101$ and $\sigma_{\text{los}}=645 \pm 69$ km s$^{-1}$ for this protocluster, respectively. Assuming virialization and spherical symmetry for the system, we estimate a total mass of $M_{\text{vir}} \sim (1-2) \times 10^{14}$ $M_\odot$ for the structure. We evaluate a number density enhancement of $g_\delta \sim 7$ for this system and we argue that the structure is likely not fully virialized at $z \sim 2.2$. However, in a spherical collapse model, $g_\delta$ is expected to grow to a linear matter enhancement of $\sim 1.9$ by $z=0$, exceeding the collapse threshold of 1.69, and leading to a fully collapsed and virialized Coma-type structure with a total mass of $M_{\text{dyn}}(z=0) \sim 9.2 \times 10^{14} M_\odot$ by now. This observationally efficient confirmation suggests that large narrow-band emission-line galaxy surveys, when combined with ancillary photometric data, can be used to effectively trace the large-scale structure and protoclusters at a time when they are mostly dominated by star-forming galaxies.

Subject headings: galaxies: clusters: general — galaxies: groups: general — galaxies: high-redshift — galaxies: evolution — galaxies: star formation — large-scale structure of universe

1. INTRODUCTION

Galaxy clusters and protoclusters at high redshifts ($z \gtrsim 2$) are ideal laboratories for studying structure formation, cosmology, and the effect of early environments on galaxy formation and evolution. The latter is particularly important as the $z \sim 2$ redshift regime traces the peak of star-formation and AGN activity in the universe (Madau & Dickinson 2014; Khostovan et al. 2015), when many physical processes, such as cold gas flow into galaxies, outflow and feedback processes, mergers, and likely environment governed the evolution of galaxies.

At low redshift, the relation between galaxy properties and environment is relatively well established. However, at high redshifts ($z \gtrsim 2$), there are conflicting results, partly due to the small number of confirmed structures, and often having only a small number of confirmed members.

At $z \gtrsim 2$, there is poor agreement between current studies on the mass-metallicity relation, with results varying from an absence of any environmental trends (Kacprzak et al. 2013), to an enhancement (Shimakawa et al. 2015), or a deficiency of metals (Valentino et al. 2013) for star-forming galaxies in denser environments. The situation is the same regarding the relation between environment and star-formation activity in galaxies at $z \gtrsim 2$ (e.g.; see Darvish et al. 2016; Shimakawa et al. 2013; Chartab et al. 2019) and the environmental dependence of the gas content of galaxies (e.g.; see Noble et al. 2017; Lee et al. 2017; Darvish et al. 2018; Hayashi et al. 2018; Wang et al. 2018; Tadaki et al. 2019). The discrepant results are likely caused by different dynamical state of the environments probed, different selection functions, small sample sizes, AGN contamination, different star formation rate (SFR), metallicity, and gas mass indicators used, complications due to extinction correction and so on. This implies the need for finding more high-$z$ structures with well-defined sample of galaxies and a large number of confirmed spectroscopic measurements.

Cluster candidates at high redshifts can be detected through the concentration of quiescent galaxies (e.g.; Strazzullo et al. 2017), by probing the environment of highly rare and active systems, such as...
There is also an extended southern section to this structure. Right panel — (B) Spatial distribution of narrow-band selected Hα emitters at z ∼ 2.23 (redshift width of ∼ 0.03-0.04) color-coded by their density enhancement. The southern section of the extended LSS (left panel) is clearly seen as an overdensity of narrow-band selected Hα emitting candidates. We perform follow-up spectroscopic observations targeting the densest region of this southern section shown with a black circle of 2 Mpc radius. The positions of the spectroscopic masks (Section 3.2) are shown with yellow rectangles. Note the z ∼ 2.1 cluster and the potential central overdensity (shown with the question mark on the left panel) are not seen here given the narrowness of the narrow-band filter.

Throughout this paper, we assume a flat ΛCDM cosmology with H₀=70 km s⁻¹ Mpc⁻¹, Ω₀=0.3, and Ωₗ=0.7. Unless otherwise stated, the transverse cosmological distances are presented as physical distances. The “physical” scale at the redshift of the protocluster (z ∼ 2.23) is ∼ 0.5 Mpc per arcmin.

2. PROTOCLUSTER SELECTION

Figure 1(A) shows the relative overdensity map in the COSMOS field for a redshift slice centered at z=2.23, with a width ±1.5σΔz/(1+z) ≈ ± 0.2 from the center of the slice (Darvish et al. 2017). The high concentration of star-forming, emission-line systems (prior to quenching) in protoclusters has been theoretically predicted by the hierarchical galaxy formation models and has successfully resulted in the spectroscopic confirmation of some protoclusters and large-scale structures (LSSs) at z ≥ 2 (e.g., Chiang et al. 2013, Lemaux et al. 2018). Therefore, large emission-line galaxy surveys can be used to effectively trace the LSSs and protoclusters at z ≥ 2.

Here, we report the spectroscopic confirmation of a protocluster, dubbed COSMOS Cluster 2.2 (CC2.2), originally found as an overdensity of narrow-band selected Ho emitters at z ∼ 2.2 in the High-Z Emission Line Survey (HiZELS) (Geach et al. 2012, Sobral et al. 2013, 2014) of the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007). In Section 2, we explain the protocluster selection. In Section 3, we present the spectroscopic observations and equip them with ancillary spectroscopic data. The protocluster properties and its fate are presented in Section 4. The results are compared with other high-z protoclusters in Section 5. We summarize the results in Section 6.
Fig. 2.— Example 2D and extracted 1D spectra showing some emission lines. Cyan lines show the 1D extraction window. The positions of Hβ, [Oii]λ4959, [Oii]λ5007, [Nii]λ6549, Hα, [Nii]λ6583, [Sii]λ6717, and [Sii]λ6731 emission lines is shown with vertical green lines for one of the galaxies. The top two spectra show two merger cases, the third one is a broad-line AGN, and the last two spectra show normal star-forming galaxies in the protocluster.

| H-band                       | K-band                        |
|-----------------------------|-------------------------------|
| mask1-24                    | z = 2.21997                   |
| mask1-18                    |                               |
| mask1-16                    | z = 2.21215                   |
| mask1-13                    | z = 2.2194                    |
| mask1-21                    | z = 2.23555                   |
| yyy                          | z = 2.22718                   |

3. SPECTROSCOPIC OBSERVATIONS

3.1. Sample Selection for Spectroscopy

To increase the success rate of our spectroscopic observations, we focus on potential targets in the vicinity of the candidate protocluster that are likely emission-line galaxies (e.g.; star-forming, starburst or AGN). This is because detecting emission lines is easier and observationally more efficient than finding absorption features in the stellar continuum which require longer integration times. Moreover, the strongest absorption features appear around the rest-frame 4000 Å which are then redshifted to the J band at the presumed redshift of the protocluster, a region populated by many atmospheric absorption and emission features.

Hence, as the primary targets in the vicinity of the overdensity, we rely on the narrow-band selected Hα emitters from the HiZELS survey (Sobral et al. 2013) in the COSMOS field at z ∼ 2.23 (Section 3.1). They are color-coded by their density enhancement defined as $\frac{\Sigma - \Sigma_0}{\Sigma_0}$, where $\Sigma$ is the surface number density and $\Sigma_0$ is the mean surface number density. This southern section stands out as an overdensity of Hα emitters (see also Geach et al. 2012). We perform follow-up spectroscopic observations with Keck/MOSFIRE targeting the densest region of this southern section as a potential protocluster (shown with a black circle in Figure 2(B)).
| Number | RA (deg) | Dec (deg) | spectroscopic z | ID(HIZELS) | ID(COSMOS) | K_s(COSMOS)a | comment |
|--------|---------|----------|----------------|------------|------------|--------------|---------|
| mask1-1| 150.184235 | 2.035242 | 2.23227 | S12B-1073 | 483880 | 21.053 | primary |
| mask1-2| 150.162308 | 1.999728 | 2.23796 | S12B-1133 | 461469 | 21.780 | primary |
| mask1-3| 150.162231 | 1.997168 | 2.2362 | S12B-1142 | 459010 | 22.225 | primary |
| mask1-4| 150.185958 | 2.009019 | - | - | 465362 | 16.753 | 2MASS star |
| mask1-5| 150.197937 | 2.026497 | 2.23767 | S12B-1089 | 478717 | 22.143 | primary |
| mask1-6a| 150.200721 | 2.023885 | 2.23675 | S12B-1149 | 457031 | 23.414 | primary |
| mask1-7| 150.201492 | 2.011835 | 2.22076 | S12B-1115 | 469074 | 22.781 | primary |
| mask1-8| 150.207275 | 2.015360 | 2.23107 | S12B-1110 | 471600 | 21.757 | primary, merger? |
| mask1-9| 150.208559 | 2.014025 | 2.24683 | S12B-1111 | 470543 | 21.507 | primary |
| mask1-10*| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-11| 150.215375 | 2.014169 | 2.23653 | S12B-1108 | 470634 | 22.683 | secondary |
| mask1-12| 150.207275 | 2.015360 | 2.23107 | S12B-1110 | 471600 | 21.757 | primary, merger? |
| mask1-13| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-14| 150.215375 | 2.014169 | 2.23653 | S12B-1108 | 470634 | 22.683 | secondary |
| mask1-15| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-16| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-17| 150.215375 | 2.014169 | 2.23653 | S12B-1108 | 470634 | 22.683 | secondary |
| mask1-18| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-19| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-20| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-21| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-22| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-23| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask1-24| 150.210721 | 2.021319 | 2.23730 | S12B-1142 | 459074 | 22.683 | secondary |
| mask2-1| 150.226868 | 2.069255 | - | S12B-9015 | 455204 | 23.440 | primary |
| mask2-2| 150.183044 | 2.077852 | 2.23340 | S12B-9096 | 451484 | 22.204 | primary, merger |
| mask2-3| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-4| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-5| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-6| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-7| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-8| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-9| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-10*| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-11| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-12| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-13| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-14*| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-15| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-16| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-17| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |
| mask2-18| 150.224147 | 1.963336 | 2.23653 | S12B-9149 | 439051 | 23.463 | primary |

aCOSMOS IDs and K_s magnitudes are from Laigle et al. 2016 catalog.
The fillers are selected to be in the vicinity of the overdensity, classified as star-forming galaxies (to increase their detection rate) based on their rest-frame $NUV - r$ vs. $r - J$ colors (Ilbert et al. 2009), with their photometric redshift in the range $1.7 < z_{\text{phot}} < 2.8$. Given their selection, some of the fillers may belong to the potential protocluster as well.

3.2. Observational Strategy

The observations were conducted on December 8, 2018 and January 13-15, 2019 with KeckI/MOSFIRE NIR multi-object spectrograph under clear conditions with the average seeing of $\sim 0.5''-0.6''$ in December and $\sim 0.3''-0.4''$ in January. Given the expected redshift of the structure, we perform observations in both $K$ ($\sim 1.92-2.40 \mu m$) and $H$ ($\sim 1.47-1.81 \mu m$) bands to cover emission lines that can later be used to measure the SFR (H$\alpha$ or H$\beta$), nebular extinction (H$\beta$ and H$\alpha$), gas-phase metallicity ([NII]6549, [NII]6583, and H$\alpha$), electron density ([SII]6717,6731 doublet), source of ionization (BPT diagram), and ionization state of the gas ([OIII]λ4959, [OIII]λ5007, and H$\beta$) for galaxies.

We designed two masks in the vicinity of the protocluster candidate (Figure 1). They were designed in such a way to maximize the number of primary targets. The masks contained unique sources except for one source that would later be used to estimate systematics. In total, we placed 30 unique primary targets and 9 fillers on the masks.

A 2MASS star per mask was used to estimate the observing conditions, such as the seeing and the spatial profile of point sources. Using an ABBA dithering pattern, we observed each mask in each filter for a total exposure time of $\sim 72$ to 96 minutes with a midpoint airmass of $\sim 1.0$ to 1.3. Using sky lines, we estimate a FWHM observed spectral resolution of $\sim 4.5$ A and $\sim 6$ A in $H$ and $K$ bands, respectively, with the slit width of 0.7''. These correspond to $R \sim 3600$ and $\delta z \sim 0.0003$.

3.3. Data Reduction

We used the MOSFIRE DRP to reduce the data. The reduction involves flat fielding, cosmic-ray removal, sky subtraction, and vacuum wavelength calibration on a slit-by-slit basis. The outputs are the 2D spectra and their uncertainties. We extract the 1D spectrum and its associated error using the optimal extraction algorithm of Horne (1986). This is done by weighted summing of fluxes in an optimized window around the 2D spectrum, where the weights incorporate both the flux uncertainties and the spatial extent of the 2D spectrum (spatial profile). To determine the optimized window, we use the spatial profile of each source. To extract the spatial profile, we collapse the 2D spectrum of each source along the wavelength direction in the vicinity of bright, high S/N features and then fit a Gaussian function to the profile. We choose the optimized window as $\pm 3 \times$ the standard deviation of the spatial profile around its center. If determining the spatial profile fails because of e.g.; faint, low S/N spectrum, we instead rely on the spatial profile of our 2MASS star. In a few cases (e.g.; nearby merging systems) where determining the optimized window is tricky, we instead extract the 1D spectra in a boxcar window wide enough to fully cover all the features (e.g.; Fig. 2 second example). Finally, for all the sources, we visually check the extraction window to make sure that the fluxes are fully measured. Figure 2 shows some example 2D and their extracted 1D spectra.

3.4. Redshift Estimation

Table 1 lists the extracted redshifts for our spectroscopic sample in the two masks, as well as the coordinate, HIZELS ID (for primary sources), $K_s$ magnitude, the COSMOS ID of each source (based on a match with the COSMOS2015 catalog with a 1'' radius), and whether a source is a primary target, a filler, a serendipitous detection, a potential merger, or a field galaxy. We report a secure redshift for galaxies that have at least two significant ($S/N > 3$) emission lines. The reported redshift is the average redshift that we obtain based on the peak of all the available emission lines for each source (mostly H$\alpha$ and [OIII]λ5007). For sources that show signs of mergers in their spectra and/or in their images (commented as “merger” in Table 1), the average redshift of different components is given.

To check for systematics in redshifts for objects on different masks, one object is observed twice (mask1-6* and mask2-14*). The extracted redshift difference for this source is $\sim 0.0003$, similar to the resolution of $\delta z \sim 0.0003$. Another primary object is also observed twice, with a serendipitous detection in the other mask (mask2-10* and mask1-91*). The extracted redshift difference for this source is zero. To check for systematics in obtaining redshifts in different bands ($H$ and $K$), we compare redshifts obtained based on emission lines in each individual band (if available). The absolute difference is in the range $\Delta z(HK) = 0.00009-0.00218$ with a median value of 0.00029, similar to the redshift resolution of $\delta z \sim 0.0003$. To further check the reliability of redshifts, for objects whose emission lines can be fitted with a single Gaussian function, we also determine redshift by fitting a Gaussian. In all cases, the extracted redshifts are within $\sim 0.0003$ of what we originally determined.

Out of 30 unique primary targets (commented as “primary” in Table 1), 29 yield secure redshifts at $z \sim 2.23$, showing the robustness of narrow-band selection (when combined with further photometric information) in tracing the LSS at high redshift. This also shows that with modest spectroscopic observations ($\sim 1-2$ hours), true high-$z$ clusters can be efficiently confirmed. We also find some fillers and serendipitous detections with spectroscopic redshifts in the vicinity of the protocluster.

3.5. Ancillary Spectroscopic Data

In the vicinity of the protocluster (150.12 $< RA$ (deg) $< 150.28$, +1.92 $< Dec$ (deg) $< +2.08, 2.21 < z < 2.25$), we find 12 sources with spectroscopic redshift measurements from the zCOSMOS-deep survey (Lilly et al. in prep, also see Lilly et al. 2009). We consider these as potential cluster members in addition to our observations. In Table 1 we denote these extra sources by the label “ancillary”.

4. PROTOCLUSTER CHARACTERISTICS

4.1. Redshift and Velocity Dispersion

To select the protocluster members, we first determine the mean redshift and standard deviation of all
unique galaxies (primary, filler, serendipitous, ancillary). Sources that are within 3 standard deviation of the mean redshift are then used to determine the new mean redshift and standard deviation. We iteratively repeat this process until a final mean redshift and standard deviation is obtained. Only three galaxies (commented as “field” in Table 1) do not pass the selection criterion. With the remaining 47 galaxies (35 from our observation and 12 from ancillary data), we estimate the mean redshift, line-of-sight dispersion in redshift space, and line-of-sight velocity dispersion as 

\[
\sigma(z_{\text{mean}}) = 0.00696 \pm 0.00074, \quad \sigma_{\text{los}} = 645 \pm 69 \text{ km s}^{-1},
\]

respectively. The uncertainties are estimated using the bootstrap method with 10,000 resamples. If we only rely on the primary sources (29 galaxies), we obtain 

\[
\sigma(z_{\text{mean}}(\text{primary})) = 0.00615 \pm 0.00073, \quad \sigma_{\text{los}}(\text{primary}) = 570 \pm 67 \text{ km s}^{-1},
\]

consistent with measurements using all the galaxies.

To investigate the role of a small sample size on the results, following Yuan et al. (2014), we randomly select only 10 galaxies from our 47 members and recalculate the velocity dispersion. We estimate the new bootstrapped velocity dispersion as 

\[
\sigma_{\text{los}}(\text{bootstrap}) = 589 \pm 149 \text{ km s}^{-1},
\]

consistent with what we found using the full sample, but with larger uncertainties. Figure 3 shows the redshift distribution, mean redshift, line-of-sight velocity distribution with respect to the mean redshift, and \(\sigma_{\text{los}}\) boundaries for our member galaxies.

4.2. Spatial Distribution

We consider the centroid of the selected protocluster members as the protocluster center at RA=150.197509 (deg) and Dec=+2.003213 (deg). The centroid is defined as the arithmetic mean of the Cartesian unit vectors representing the protocluster members. For a 2D Gaussian distribution, \(~40%\) of the weight of the distribution is within one standard deviation. Hence, we use the projected radius from the protocluster center that contains 40% of the members as a proxy for the typical radius of the core of the protocluster and estimate it to be \(R_{\text{proj}} = 0.75 \pm 0.11 \text{ Mpc}\). Using only primary sources, we obtain RA(primary)=150.208397 (deg), Dec(primary)=+2.000796 (deg), and \(R_{\text{proj}}(\text{primary}) = 0.65 \pm 0.13 \text{ Mpc}\). Fig 4 (A) shows the spatial distribution of the members. In Fig 4 (B), they...
Fig. 4.— Top panel — (A) Three-color RGB image in the vicinity of our protocluster CC2.2. Yellow circles show the spatial distribution of the members. The green circle corresponds to the $R_{proj}$ of the protocluster. The red, green, and blue channels correspond to the UltraVISTA $K_s$, $J$, and $Y$ bands, respectively (McCracken et al. 2012). Bottom panel — (B) Spatial distribution of the protocluster members (circles are primaries, triangles are fillers and serendipitous sources, and squares are ancillary sources) color-coded by their line-of-sight velocities with respect to the mean redshift. The primary sources not observed (here in this paper or as ancillary) are shown with empty circles. The positions of the spectroscopic masks are shown with dashed rectangles. The plus sign shows the protocluster center. The dashed circle shows the estimated $R_{proj}$ of the protocluster. The multiplication sign shows the position of a candidate cluster (SACS-COSMOS-J100052+020018, Rettura et al. in prep.) seen as an overdensity of Spitzer-detected galaxies, reinforcing the reality of the structure.
are color-coded by the line-of-sight velocities relative to the mean redshift of the protocluster. We find that 51(87)% of members are within 1(2) Mpc from the protocluster center.

The match to COSMOS2015 catalog shows that three of the members, mask1-1, mask1-15, and mask1-16 have Chandra X-ray detections (Elvis et al. 2009; Civano et al. 2016; Marchesi et al. 2016). This comprises 6.8±3.7% (6.9±4.9%) of the members (primary members), a factor of ≈ 4 larger than the overall fraction of X-ray detected Hα emitters in the HIZELS/COSMOS field at z = 2.23 (Callau et al. 2017). All three have broad emission lines, indicative of their AGN nature and they are all Lyα emitters as well (Matthee et al. 2016; Sobral et al. 2017). The enhanced fraction of X-ray detected AGN in the protocluster relative to the field is in good agreement with Lehner et al. (2013), mask1-16 also has a VLA 20 cm radio detection (Schinnerer et al. 2010). These indicate that highly rare and active systems, such as extreme X-ray sources and radio galaxies trace dense environments at high-z, further supporting the dense nature of the protocluster. A detailed analysis of the AGN fraction will be presented in a following paper.

4.3. Dynamical Mass

One major difference between protoclusters and clusters, as discussed in e.g., Diener et al. (2015) and Wang et al. (2016), is that protoclusters are not yet fully virialized. Hence, for such non-virialized systems, the velocity dispersion is mainly an indicator of the dynamical state of the system rather than the halo mass. Therefore, any estimation of the dynamical mass based on the velocity dispersion for non-virialized systems should be considered as order-of-magnitude estimates and should be used with caution.

If we assume that the protocluster is virialized (see Section 4.4) and σ₃d and Rₜₚₙₑᵦ are the total velocity dispersion and characteristic radius of the protocluster’s core, then we can estimate its virial mass from the virial theorem as $M_{vir} = R_{proj} \sigma_{3d}^2 / G$, where G is the gravitational constant. Assuming a spherical symmetry, $\sigma_{3d}^2 = 3 \sigma_{los}^2$. Substituting $R_{proj}$ and $\sigma_{los}$ into the equation gives $M_{vir} = (3 R_{proj} \sigma_{los}^2 / G) = (2.2 \pm 0.6) \times 10^{14} M_\odot$. With primary sources, we obtain $M_{vir}(primary) = (1.5 \pm 0.5) \times 10^{14} M_\odot$.

We can alternatively estimate the virial mass if we assume that the virial theorem applies to the protocluster and the halo of the protocluster is a spherical region within which the average density is $200 \rho_c(z)$, where $\rho_c(z)$ is the critical density of the universe at redshift of $z$ (Navarro et al. 1997). Then, we can express the virial mass ($M_{200}$) of the protocluster in terms of its virial radius $r_{200}$ and the critical density as $M_{200} = 4 \pi r_{200}^3 \rho_c(z)$. The critical density can be expressed in term of the Hubble parameter ($H(z)$) as $\rho_c(z) = 3 H^2(z) / 8 \pi G$. Assuming a spherical symmetry combined with the virial theorem implies $r_{200} = GM_{200} / (3 \sigma_{los}^2)$. Therefore, we can express $r_{200}$ and $M_{200}$ as functions of $\sigma_{los}$ and $H(z)$ as $r_{200} = \sqrt[3]{3 \sigma_{los}^2 / (10 H(z))}$ and $M_{200} = (3 \sigma_{los}^2 / 10 GH(z))$ (Carlberg et al. 1997). We estimate $r_{200} = 0.49 \pm 0.05$ Mpc and $M_{200} = (1.4 \pm 0.5) \times 10^{14} M_\odot$. Using only primary sources, $r_{200}(primary) = 0.43 \pm 0.05$ Mpc and $M_{200}(primary) = (1.0 \pm 0.3) \times 10^{14} M_\odot$. These are in good agreement with $R_{proj}$ and $r_{vir}$ found above.

The Spitzer Archival Cluster Survey (SACS) is a comprehensive search for distant galaxy clusters in all Spitzer/IRAC extragalactic pointings available in the Spitzer/IRAC extragalactic pointings available in the mission archive (Rettura et al. 2019 in prep.). Using the algorithm described in Rettura et al. (2014), high-redshift clusters are identified as overdensities in the mid-infrared data combined with shallow all-sky optical data. We find a match in their catalog (at a similar redshift), cluster SACS-COSMOS-J100052+020018, separated by only $\sim 1.2'$ from our protocluster. The position of their candidate is shown with a multiplication sign in Figure 4. This provides further confirmation for the existence of the detected structure as Rettura et al. use a completely independent approach in finding high-$z$ proto clusters. Based on a relation calibrated in Rettura et al. (2018) (see their Eq. 6), they use the Spitzer 4.5 μm richness of their clusters to infer their dynamical mass. This candidate cluster has an estimated mass, $log(M_{500}/M_\odot) = 14.06 \pm 0.25$, consistent with our estimate based on the velocity dispersion.

Using simulated clusters, Munari et al. (2013) suggest a scaling relation as $M_{200}/10^{14} M_\odot = (\sigma_{1D}/A_{1D})^{-\alpha}/h(z)$, where $A_{1D}$ and $\alpha$ are two parameters, $\sigma_{1D}$ is the 1D velocity dispersion, and $h(z) = H(z)/H_0$. According to their Figure 3, $A_{1D} \sim 1185 \pm 30$ km s⁻¹ and $\alpha \sim 0.38 \pm 0.01$ at $z = 2$ using galaxies as a tracer for the total mass of clusters. With this scaling relation, we obtain $M_{200}(scaling) = (3.8 \pm 0.2) \times 10^{14} M_\odot$, a factor of $\sim 3$ larger than $M_{200}$ we found before but within the same order of magnitude.

We note again that we have made a number of assumptions, such as virialization and the spherical symmetry in estimating the dynamical quantities. These assumptions may not be entirely correct, particularly for protoclusters at high redshift as they are likely still forming (see Section 4.4). Therefore, these should be considered as order-of-magnitude estimates of the protocluster mass. However, in a following paper, we will present an agreement with Lehner et al. (2013).

4.4. Protocluster’s Fate

Is the protocluster relaxed and fully virialized by the time of observation ($z \sim 2.23$)? The redshift distribution is not symmetrically Gaussian (skewness = -0.5262,

| quantity | all members | primary members only |
|----------|-------------|----------------------|
| RA(deg)  | 150.197509  | 150.288397           |
| Dec(deg) | +2.003213   | +2.000796            |
| z mean   | 2.232242±0.00101 | 2.233212±0.00113     |
| $\sigma_{los}$ (km s⁻¹) | 645±69     | 570±67               |
| $R_{proj}$ (Mpc) | 0.75±0.11  | 0.65±0.13            |
| $M_{vir}(10^{14} M_\odot)$ | 2.2±0.6    | 1.5±0.5              |
| $r_{200}$ (Mpc) | 0.49±0.05  | 0.43±0.05            |
| $M_{200}(10^{14} M_\odot)$ | 1.4±0.5    | 1.0±0.3              |
although the difference from a normal distribution is at
< 1.6 σ significance level) and the line-of-sight velocities
with respect to the mean redshift are not fully symmetric
(Figure 3), indicating that the structure is still in the
assembly process. As shown in Figure 1 the presence of
other potential overdensities and filamentary-like structures
in the vicinity of the protocluster further suggests
that the structure is likely not relaxed at $z \sim 2.23$ and
still coalescing.

We estimate the dynamical timescale ($\tau_{\text{dyn}}$) of the
protocluster. The protocluster could be virialized at $z \sim
2.23$ if at least one dynamical timescale (in practice, a
few) has elapsed since its formation. We estimate $\tau_{\text{dyn}} \sim
r_3/\sigma_3$, where $r_3$ is the characteristic radius of the
protocluster and $\sigma_3$ is its total velocity dispersion. If we
assume $r_3 \sim R_{\text{proj}}$ and the spherical symmetry and use
the estimated line-of-sight velocity dispersion and $R_{\text{proj}}$
from Section 4.1 we obtain $\tau_{\text{dyn}} \sim 0.75$ Mpc$/\sqrt{3} \times 645$
$$ \text{km s}^{-1} \sim 0.6 \text{ Gyr}. $$ Therefore, if the protocluster was
initially formed prior to $z \sim 2.8$, it would have had suffi-
cient time to get virialized by the time of observation.

Estimating the formation epoch of the protocluster is not
straightforward. However, the average age of the stellar
populations of its member galaxies, particularly the quies-
cent systems can place robust constraints on its forma-
tion time. By selection, quiescent galaxies are currently
missing in our spectroscopic observation. However, fu-
ture deep follow-up spectroscopic observations of poten-
tial passive galaxies in the protocluster can put stringent
constraints on its formation epoch.

Is the protocluster relaxed by now ($z=0$)? To answer
this, we investigate the evolution of the protocluster over-
density in the linear regime of a spherical collapse model
and compare it with the critical collapse threshold of
$\delta_c = 1.69$ \footnote{We note that this value of linearly-extrapolated critical den-
sity enhancement is for an Einstein-de Sitter cosmology. However,
it has been shown to have a weak dependence on cosmological
models \cite{Percival2005}.}.

Within a redshift slice of $\Delta z \sim 0.03$ (width
of the narrow-band filter) and a projected 2 Mpc ra-
dus circle placed at the center of the protocluster, we
find 35 Hα emitters (the original sample from which the
primary targets were selected for spectroscopy). The
average number of Hα emitters in the same volume is
$\sim 4.6$ (corrected for the effective area of the survey and the
enhancement due to the overdensity). Therefore, using
narrow-band selected Hα emitters, the galaxy number
density enhancement is
$$ \delta g = \frac{\delta n}{\delta n_{\text{obs}}} \sim 6.6. $$

Following Steidel et al. \cite{Steidel2005}, $\delta g$ is related to the mass
density enhancement ($\delta_m$) via $1+b \delta_m = C(1+\delta_g)$, where $b$
is the clustering bias and $C$ is a correction term due to the
redshift space distortions and is calculated using $C=1+f-
f(1+\delta_m)^{-1/3}$, where $f=\Omega_m(z)^{0.6}$. Using $f(z=2.23) = 0.96$
and the clustering bias of $b=2.4$ for the Hα emitters at $z
\sim 2.23$ \cite{Geach2012}, we obtain $\delta_m(z=2.23) \sim 1.61.$

In a spherical collapse model \cite{Mo1996}, this is related to a linear matter enhancement of
$\delta_{\text{f}}(z=2.23) \sim 0.73$ and is expected to grow to $\delta_{\text{f}}(z=0) \sim 1.9$ by
$z=0$. This exceeds the collapse threshold of $\delta_c = 1.69.$
Therefore, the protocluster is expected to fully collapse
and virialize by now ($z=0$). In fact, the linear mat-
ner enhancement reaches the collapse threshold at $z \sim
0.1$, indicating that the protocluster should have been
virialized since the past $\sim 1.0-1.5$ Gyr. The collapse
threshold at any redshift is approximated as $\delta_c(z) \approx
1.69D(z)/D(z)$, where $D(z)$ is the linear growth func-
tion \cite{Percival2005}. At the redshift of the protocluster,
$\delta_c(z=2.23) \sim 4.3$. This is larger than $\delta_{\text{f}}(z=2.23)$,
further indicating that the structure is likely not virialized
at $z=2.23$.

We estimate the virialized mass of the protocluster
at present $M_{\text{dyn}}(z=0)$ through $M_{\text{dyn}}(z=0) =
\rho_m(V_{\text{obs}}/C)(1 + \delta_m)$, where $\rho_m$ is the mean comoving
density, $V_{\text{obs}}$ is the observed comoving volume of the
structure, and $C$ is the correction term introduced above
\cite{Steidel1998}. The Hα emitter candidates are dominated by those selected in UKIRT/WFCAM
narrow-band K filter \cite{Sobral2013}. Assuming a
tophat shape for the filter corresponds to a redshift width
of $\Delta z \sim 0.032$ centered at $z \sim 2.23$. The corre-
sponding comoving radial width ($\Delta V$) is then $\sim 42$ Mpc.
This leads to the comoving $V_{\text{obs}} \sim 5500$ Mpc$^3$ for a
$\Delta z \sim 0.032$ centered at $z \sim 2.23$. Given $\delta_m(z=2.23) \sim 1.61$ and $C=0.64$, we esti-
mate $M_{\text{dyn}}(z=0) \sim 9.2 \times 10^{14} M_\odot$. Therefore, the
protocluster is likely the progenitor of a Coma-type cluster
at $z=0$. Simulations of \cite{Chiang2013} show that
at $z > 2$, the progenitors of a Coma-type cluster traced
by SFR $> 1 M_\odot$/yr$^{-1}$ galaxies are expected to have a
galaxy density enhancement of $\delta_g \sim 5.5^{+5.5}_{-3.8}$ probing over
$15^{3} \sim 3500$ Mpc$^3$ comoving volumes. These values are
in rough agreement with our measurements, indicating that
our protocluster is expected to evolve into a $\sim 10^{15}
M_\odot$ Coma-type cluster at $z=0$.

The comoving volume associated with Hα emitter can-
didates in the HiZELS/COSMOS field is $\sim 5.48 \times 10^{5}$
Mpc$^3$ \cite{Sobral2013}. Given the detection of one
protocluster in this volume, we estimate a comoving space
and mass density of $\sim 1.8 \times 10^{-6}$ Mpc$^{-3}$ and $\sim
(1.8 - 3.6) \times 10^{6} M_\odot$ Mpc$^{-3}$ for a $M_{\text{dyn}} \sim (1 - 2) \times 10^{14}
M_\odot$ protocluster at $z \sim 2$. However, we note that Poisson
uncertainties are as large as the reported values. With
the Poisson uncertainty, the space density of the protocluster
is $\lesssim 3.6 \times 10^{-6}$ Mpc$^{-3}$. The halo mass function
of \cite{Bocquet2010} predicts a space density of $\sim 1-
2 \times 10^{-7}$ Mpc$^{-3}$ for a $M_{200} \sim 10^{14} M_\odot$ halo at $z=2$, a
factor of $\sim 10$ smaller than our estimate, but consistent
with it given the large Poisson uncertainty in our mea-
surement. Moreover, for a sample of similarly selected
Hα emitters in the UDS \cite{Sobral2013} and Böotes
\cite{Matthee2017} fields at $z \sim 2.2$ with comoving
volumes of $\sim 2.24 \times 10^{5}$ Mpc$^3$ and $\sim 2.7 \times 10^{5}$ Mpc$^3$, respectively, no overdensity of Hα emitters is found. This
increases the effective volume and subsequently decreases
the space density of our protocluster, making our mea-
surement more consistent with the halo mass function
predictions.

5. COMPARISON

We compare the present-day mass of $z \gtrsim 1.5$
protoclusters compilation from \cite{Overzier2019} with
that of our protocluster. The median protocluster
in the compilation has a present-day mass of
$log(M(z=0)/M_\odot) = 14.6$. This makes our
protocluster one of the most massive systems with a $z=0$
mass comparable to some remarkable high-$z$ protoclus-
6. SUMMARY

We report the spectroscopic confirmation of a new protocluster in the COSMOS field at z ≈ 2.45, dubbed “Hyperion”, containing at least seven density peaks with masses in the range ~ (0.1-2.7)×10^14 M_☉. Hyperion is extended over a comoving volume of ~ 60×60×150 Mpc^3 and has an estimated total mass of ~ 4.8×10^{15} M_☉. Could the extended LSS shown in Figure 1 (A) be a super-protocluster similar to “Hyperion”? The comoving radial distance between the northern cluster at z ≈ 2.1 and our protocluster in the south is ~ 180 Mpc. If the extended structure (including the central overdensity shown with a question mark and other potential surrounding overdensities) is confirmed to be a multi-component super-protocluster, it would have a comoving volume of ~ 40×40×180 Mpc^3, making it comparable to Hyperion. Follow-up spectroscopic observations could further reveal the nature of this structure.

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