Multi-Wavelength Follow-up of the High-z COBRA Cluster Survey

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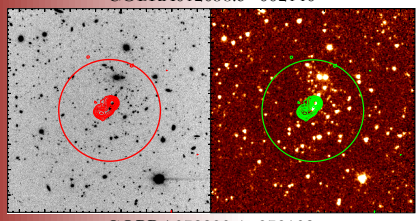
Galaxy clusters offer a unique laboratory for studying galaxy evolution from early in the universe to the present day. However, few high-z, spectroscopically confirmed galaxy clusters are known. Recent techniques including infrared overdensity searches and AGN targeting show promising results in revealing new distant clusters. Here, we present results from the **Clusters Occupied by Bent Radio AGN (COBRA)** survey of high-z galaxy clusters, which combines optical, IR, radio, and X-ray observations. The COBRA survey consists of 646 bent, double-lobed radio sources selected from the VLA FIRST Survey and extends up to z ~ 3.0. The bent radio morphology results from interactions between the AGN host galaxy and the surrounding intracluster medium – the relative motion results in ram pressure on the lobes, bending them. Since low-z bent, double-lobed radio sources are found to frequently reside in clusters and the radio emission is easily detected at high-z, these sources are ideal tracers for high-z clusters. We measure galaxy overdensities with our *Spitzer* observations, and find that approximately 40% of our sources are cluster candidates. We have followed many of these sources up with optical observations at the Discovery Channel Telescope. Additionally, some of our targets have been detected in the X-ray. Here, we present initial results from the COBRA survey, which include some of the highest-z cluster candidates known. Future Chandra observations of these targets will lend insight into the evolution of X-ray properties in clusters, including the effects of AGN feedback.

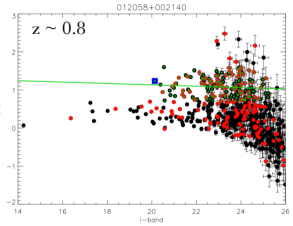
The High-z COBRA Survey

- The survey includes 646 bent, double-lobed radio sources selected from the VLA FIRST Survey of which all have been followed up in the IR with *Spitzer*.
- The redshift estimates range from $0.5 < z < 3.0$.
- Each radio source lacked an SDSS host to a limit of $m_r = 22$.
- We are following these sources up with deep optical observations with the 4.3 m Discovery Channel Telescope (DCT).
- The red sequence has been identified out to z ~ 1.8, and should be identifiable on our color magnitude diagrams (Andreon et al. 2014).
- At z > 1, the 4000Å break should fall between the i and 3.6μm bands.

Wavebands	Sources Observed
Spitzer IRAC 3.6 μm band	646
Spitzer IRAC 4.5 μm band	135
DCT observations with SDSS i-band	62
DCT observations with SDSS r-band	38

COBRA012058.9+002140





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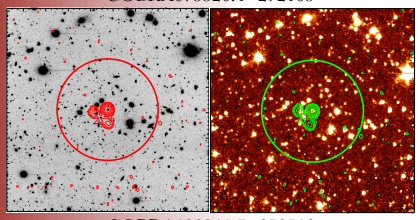

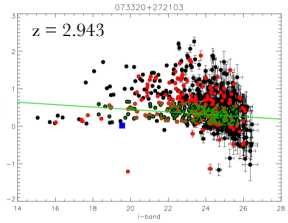

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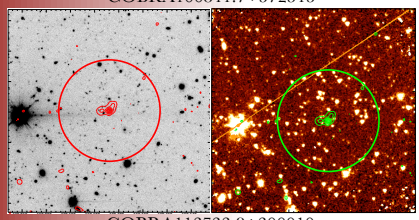
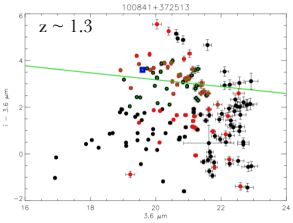
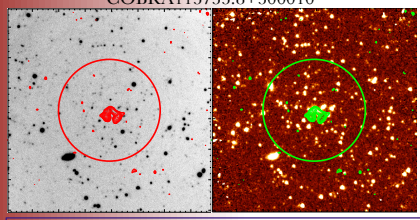
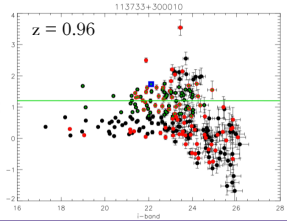




COBRA113733.8+300010





- The DCT i-band (left panel) and *Spitzer* 3.6 μm (right panel) images above are example COBRA cluster candidates.
- The circles have 1' radii and the 20 cm radio contours from FIRST are superposed.
- Example color magnitude diagrams show sources within 1' of the host in red, sources within 2' in black, the host galaxy in blue, and the red sequence fit and galaxies included in the fit in green.
- The redshifts for COBRA113733.8+300010 and COBRA073320.4+272103 are based on spectroscopic redshifts of their host galaxies and COBRA0733020.4+272103 is a quasar.

Analysis/Results

- Cluster candidates are identified based on a 2σ overdensity in the 1' or 2' region surrounding the radio host.
- For the 3.6μm fields, the overdensity was compared to the normalized SpUDs field, while for the r and i-band observations, it was measured locally (Paterno-Mahler et al. in prep, Golden-Marx et al. in prep).
- 399 of the targets have a positive excess of galaxies compared to the background and 238 of these are overdense at the 2σ level and thus are cluster candidates (Paterno-Mahler et al . in prep).
- Using our multi-wavelength observations, we estimate photometric redshifts by modeling the color of the host galaxy with EzGal models (Bruzual & Charlot (2003) SPS model, z_f=3, & Salpeter IMF).
- A best-fit photometric redshift is found by minimizing the difference between our measured host colors and the modeled colors (Golden-Marx et al. in prep).
- To find the red sequence, we follow the methodology of Cooke et al. (2016) by removing the blue stellar portion of our CMDs and iteratively fitting the red sequence with successive 1.5σ cuts until the sample remains constant.
- Of the 238 cluster candidates, 32 have redshift estimates $0.5 < z < 0.7$ and 149 have redshift estimates $z > 0.7$.

COBRA113733.8+300010

- The right image shows a Chandra X-ray image (blue) with *Spitzer* 3.6 μm image (red) and 20 cm radio contours.
- The bold yellow circles and lines mark galaxies that are spectroscopically confirmed at z = 0.96. Other cluster members are marked with thin, white circles.
- The cluster was detected in the X-ray at the 6σ level in a 20 ksec exposure with Chandra and has $L_x = 2 \times 10^{44}$ erg/s.