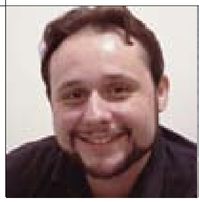


by Adam Muzzin
& Howard Yee

Spectroscopy of High-Z Galaxy Clusters with Band-Shuffle

Rich clusters of galaxies are some of the most spectacular objects in the universe. They are the largest gravitationally bound structures, containing hundreds of massive galaxies and thousands of smaller ones all whizzing around at thousands of kilometers per second within a relatively compact 10 to 20 cubic megaparsecs. Staring at Hubble Space Telescope images of nearby clusters is a constant reminder of just how small we are compared to the rest of the universe.

It is well known that the galaxies in clusters are different from those that aren't in clusters–which are typically referred to as "field" galaxies. Clusters contain massive galaxies that are non-star-forming, usually elliptical or type S0, whereas field galaxies are often less massive, spiral-shaped, and have star-forming regions. For decades, astronomers have been trying to understand why the cluster population is so different from the field population, but no consensus has emerged yet. We know the differences are probably related to the cluster environment, which contains hot x-ray-emitting gas, experiences high-speed encounters between galaxies, and shows extreme tidal effects from the huge dark-matter halo. Yet, we are uncertain about exactly how these factors alter the cluster galaxy population.

An obvious way to get a better handle on the problem is to observe the most distant clusters, meaning those at $z > 1$, to see how their galaxies differ from nearby clusters, as well as their counterparts in the field at $z > 1$. Galaxies are more active at higher redshifts, which should further highlight the contrast between cluster and field populations.

But, before high-redshift clusters can be observed, we have to find them. It's hard work. The intra-cluster gas in distant clusters is faint in the x-ray regime because of surface-brightness dimming that scales as $L_x \sim (1 + z)^{-4}$. Cluster galaxies are also faint, and Doppler-shifting means most of their light is not received at optical wavelengths, but in the infrared. As a result, deep x-ray or infrared surveys are needed to detect distant clusters—both of which are still hard to come by these days.

In addition to the need for deep observational data, rich clusters of galaxies are rare objects. Current lambda cold dark matter (λCDM) halo models predict about one Coma-mass cluster ($M \sim 10^{15}\ M_{Sun}$) at $z > 1$ in every 50-100 square degrees of sky. Even clusters half that massive only occur once in every 2 - 4 square degrees of sky surveyed. Putting it all together, we need to have both deep- and wide-field surveys to find distant clusters.

The SPARCS Survey

Given the observational challenges, it should come as little surprise that the number of confirmed massive clusters at $z > 1$ is still quite small: around 10-30, depending on the definitions of "confirmed" and "massive." In 2005, the public release of the Spitzer Wide-area InfraRed Extragalactic legacy survey (SWIRE) from the Spitzer Space Telescope presented a golden opportunity to look for more clusters using infrared/optical methods. At 50 square degrees, SWIRE occupies a unique parameter space. It is a wide enough field to find a significant population of massive $z > 1$ clusters, and, due to Spitzer's power in the infrared, it also reaches deep enough to reliably select $z > 1$ candidate clusters.

To take advantage of the large SWIRE area, we decided to use the well-proven Cluster Red-Sequence (CRS) method that looks for clusters as over-densities of galaxies in a combined color-position space. This method has been used extensively to look for clusters up to $z \sim 1$ in the 100-square-degree RCS-1 survey and the next generation 1000-square-degree RCS-2 survey. We conducted a deep survey of SWIRE in the *z*-band in order to use a combined *z* - 3.6-micron color to select clusters at $z > 1$. This project, the Spitzer Adaptation of the Red-sequence Clusters Survey (SpARCS), was the first to try to employ the CRS method to select $z > 1$ clusters using infrared data; it remains the largest such survey for $z > 1$ clusters to date. The survey contains several hundred candidate clusters at $z > 1$, with estimated masses between $\sim 5 \times 10^{13}\ M_{Sun}$ and $1 \times 10^{15}\ M_{Sun}$.

Spectroscopic Confirmation of SpARCS Clusters With Band-Shuffle on Gemini

To prove that SpARCS is selecting real clusters, we wanted to confirm the redshifts and masses of some of our candidate clusters with spectroscopy. However, obtaining redshifts and velocity dispersions for $z > 1$ clusters is observationally intensive work. Even at $z > 1$, where most galaxies are forming stars, cluster galaxies are still frequently devoid of emission lines, requiring long exposures to obtain high signal-to-noise on the continuum to detect absorption features. Furthermore, their extreme distances mean that even massive clusters are small in angular size, with most of their galaxies appearing in an area of sky that is only about 1-2 arcminutes across.

As an example, the left panel of Figure 1 (next page) shows a color image of a massive $z = 1.157$ cluster in a 6 × 6 arcminutes field of view (f.o.v.)—roughly the f.o.v. of the Gemini Multi-Object Spectrograph (GMOS) and other multi-object spectrographs. Canonical multi-object spectroscopy (MOS) requires long slits, ~ 10 arcseconds long, in order to facilitate the subtraction of sky lines, which means even in ideal cases a typical mask can only get 6-12 slits across the central region of distant clusters, a pretty dismal return of cluster galaxy spectra per mask.

The nod-and-shuffle (N&S) mode available on GMOS offers a major improvement in slit placement over regular MOS modes. Because targets are nodded across the slit for sky subtraction, the required length of the slit is only two to three times the angular size of the object. For distant galaxies, typically ~ 1 arcsecond across, it means only requiring slits ~ 3 arcseconds across. This provides a major gain over the typical 10 arcseconds long slits. There are two observing modes in which N&S observations can be performed: "micro-shuffle" and "band-shuffle". The majority of N&S spectroscopy with GMOS (such as the Gemini Deep Deep Survey (GDDS)) has been done in the micro-shuffle mode, where shuffled charges are stored directly above or below the location of the slit. This means a 3-arcseconds slit requires a blank space of 3 arcseconds above or below it to store shuffled charge, increasing the effective slit area to 6 arcseconds. This is still better than conventional spectroscopy, but is not ideal for clusters.

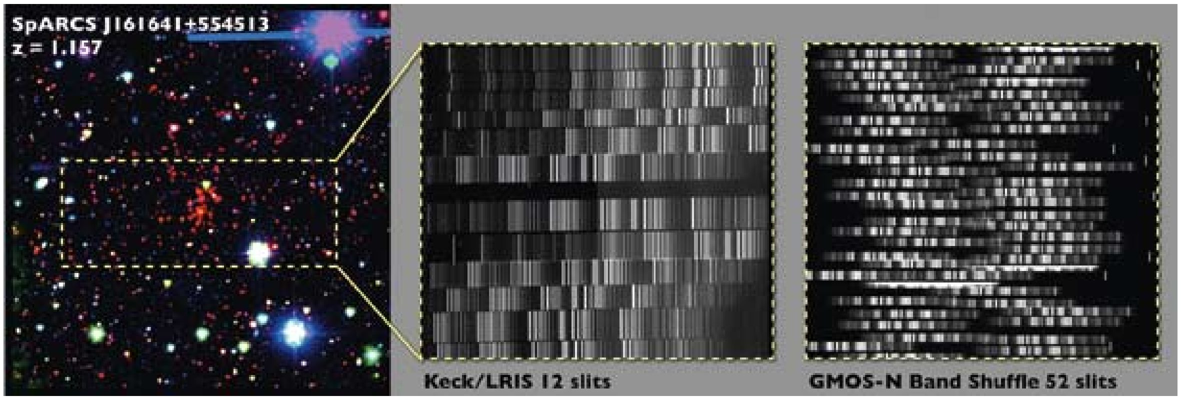

Figure 1.
Left Panel: A g,z, 3.6μm color image of the cluster SpARCS J161641+554513 at z = 1.157. The field of view (f.o.v.) of the image is 6 × 6 arcminutes, approximately the f.o.v. of GMOS. The yellow boxed area shows the region that can be used for "band-shuffle" observations. Middle Panel: Spectra within the band-shuffle region, from a spectroscopic mask observed with LRIS on Keck. Right Panel: Spectra from a band-shuffle mask on GMOS. The 3× smaller slit length from N&S, combined with a band-limiting filter, allowed 52 slits to be fit within the region, making GMOS about 4 times more efficient than LRIS for obtaining spectra of cluster galaxies at z ~ 1.

In band-shuffle mode, the entire central region of the chip is shuffled to the top or bottom of the chip, which means no space is required between slits. While it is technically less efficient in the total use of the GMOS chips (only one third of the area is used, whereas up to half can be used with micro-shuffle), it is perfect for high-*z* clusters. With a band-limiting filter we can now typically place 35 - 55 slits within an area of about 3.0 × 1.7 arcminutes around these clusters.

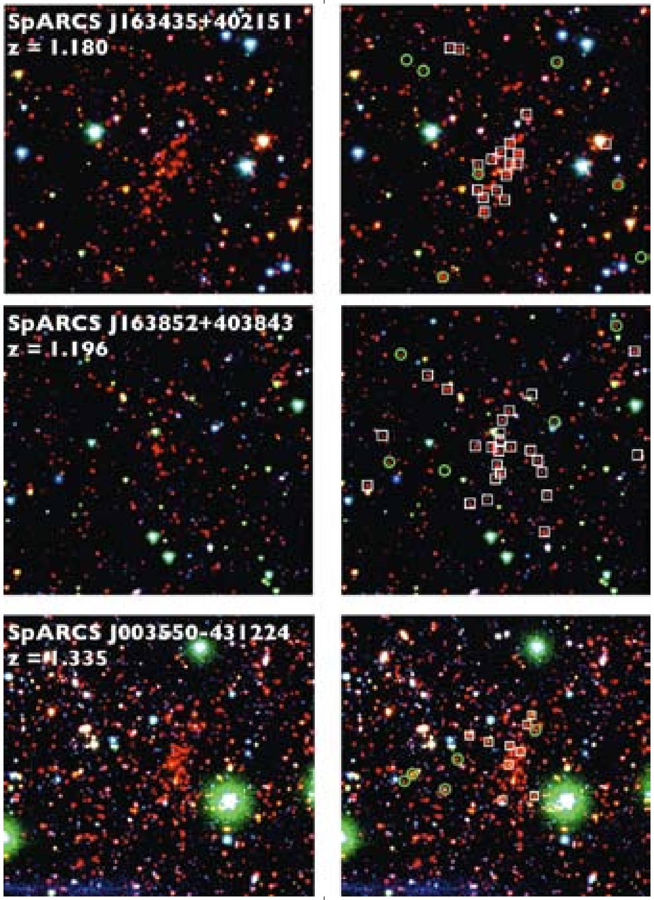

Figure 2.
Left Panels: g,z, 3.6μm color images of three z › 1 clusters from the SpARCS survey with redshifts and masses confirmed by GMOS observations. Right Panels: Same as left panels, with white squares representing confirmed cluster members, and green circles representing confirmed foreground and background galaxies. These clusters are the most distant discovered with the CRS method to date and are some of the most distant galaxy clusters known.

In the middle panel of Figure 1 we show a spectroscopic mask observed using conventional MOS with LRIS on Keck. The right panel shows one of our GMOS band-shuffle masks. Note the considerable efficiency of GMOS over LRIS in packing in the slits using band-shuffle mode.

GMOS has been a critical tool for confirming both the redshifts and masses of the first $z > 1$ cluster candidates in the SpARCS survey. In Figure 2 we show images of three SpARCS clusters, all confirmed with GMOS. SpARCS J003550-431224 at $z = 1.335$, in particular, is an important find. It is currently one of the most distant known clusters and is by far the most distant cluster detected with the CRS method, demonstrating that the highly efficient two-filter CRS method works extremely well for finding massive clusters, even out to the highest redshifts.

Next Step: Gemini Cluster Astrophysics Spectroscopic Survey (GCLASS)

After our initial observing runs with GMOS, we quickly realized how powerful the instrument would be for a detailed follow-up study of distant clusters. Individual $z > 1$ x-ray and optical/infrared selected clusters have been studied; however, no survey of a large sample of rich $z > 1$ clusters has been done. The size of the SpARCS survey meant that we had numerous rich $z > 1$ clusters that could be followed up in detail.

As of semester 2009B, we are now halfway through observations for the Gemini Cluster Astrophysics Spectroscopic Survey (GCLASS). This large, 200-hour project aims to obtain spectra of 50 galaxies in 10 rich clusters at $0.87 < z < 1.34$ selected from the SpARCS survey, making it the state-of-the-art distant cluster project. The scope of the science covered by the project is large. Here are

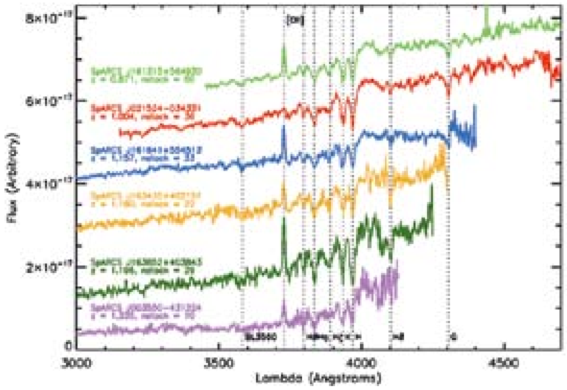

Figure 3.
Rest-frame stacked spectra of the average galaxy in six out of ten clusters in the GCLASS project. Prominent spectral features such as [OII] emission and hydrogen Balmer absorption are (Hδ, Hζ, Hη, Hθ) marked. The clusters show a diverse range in [OII] emission-line strength and Balmer absorption, which clearly shows the importance of a large sample of clusters in understanding their stellar populations.

some highlights: the first measurement of accurate dynamical masses for a sample of $z \sim 1$ clusters, which will be a crucial factor in studying dark energy with cluster abundances; the first measurement of the average mass and light profile of a massive dark matter halo at $z \sim 1$, from "stacking" the velocity data on the clusters; and a extensive look at the stellar populations of galaxies in a sample of homogenously-selected rich clusters at $z \sim 1$.

In Figure 3 we plot stacked spectra of cluster members from the first ~40 percent of observations from the GCLASS project. With only a few of the masks on about half of the clusters, a significant diversity in both the strength of the [OII] line (typically from star formation) and the Hδ line (typically an indicator of a "post starburst" phase) can already be seen. Figure 3 not only demonstrates the exquisite quality of spectra that can be obtained for distant galaxies using N&S, but also shows the cluster-to-cluster variations in the stellar populations of their galaxies. From Figure 3, it is already clear that to get a fair sample of galaxies in distant clusters, a sample of 10 or even more clusters is crucial.

The prospects are bright for GMOS N&S spectroscopy on these clusters, and I look forward to summarizing the results from the GCLASS survey in a future article. Observations for GCLASS are expected to conclude in semester 2010B.

The work presented in this article has been done in close collaboration with Gillian Wilson (University of California, Riverside) who serves as PI of the SpARCS/GCLASS projects. The SpARCS/GCLASS team consists of 26 members from 19 institutions.

For more information see:

Muzzin, A., *et al.* 2009, *ApJ*, **698**, 1934

Wilson, G., *et al.* 2009, *ApJ*, **698**, 1943

Eisenhardt, P., *et al.* 2008, *ApJ*, **684**, 905

Stanford, S. A., *et al.* 2006, *ApJ*, **646**, L13

Muzzin, A., Wilson, G., Lacy, M., Yee, H.K.C., & Stanford, S. A. 2008, *ApJ*, **686**, 966

Gladders, M. D. & Yee, H.K.C. 2005, *ApJS*, **157**, 1

Gladders, M. D. & Yee, H.K.C. 2000, *AJ*, **120**, 2148

Adam Muzzin is a postdoctoral associate at Yale University. He can be reached at: adam.muzzin@yale.edu

Howard Yee is professor of astrophysics at the University of Toronto. He can be reached at: hyee@astro.utoronto.ca