**NOAO Observing Proposal** *Standard proposal* **Panel:** *For office use.*
*Date:* September 27, 2012 **Category:** Clusters of Galaxies

# Uncovering the Distribution of Star Formation in z=0.25 Galaxy Clusters

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**Abstract of Scientific Justification** *(will be made publicly available for accepted proposals)***:**
We propose to use the Rhoads 820R (k1047) and WR CIII (k1021) filters to detect both the H$\alpha$ and O[II] emission from star-forming galaxies in three rich galaxy clusters at $z = 0.25$: Abell 1835, Abell 2070, and Abell 992. We will measure star formation rates as low as 0.2 solar masses/year from the H$\alpha$ narrow band flux excess for galaxies as faint as $i_{AB} = 24.0$, using the coincidence of two narrow band flux excesses to confirm cluster membership. This will allow us to extend measurements almost an order of magnitude lower in star formation rate and two magnitudes fainter in galaxy luminosity over the current limits obtained for intermediate-redshift clusters. Using the coincidence of both filters will allow us to efficiently exclude line emission from background galaxies while capturing star formation from 60% to 80% of the cluster galaxies. We will study the spatial distribution of the star formation in these faint cluster members as a way of experimentally determining the effect of the intra-cluster environment on these galaxies and to obtain a complete picture of star formation in these clusters.

**Summary of observing runs requested for this project**

| Run | Telescope | Instrument | No. Nights | Moon | Optimal months | Accept. months |
|---|---|---|---|---|---|---|
| 1 | KP-4m | MOSA | 3 | grey | Mar - May | Feb - Jul |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |

**Scheduling constraints and non-usable dates** *(up to four lines).*

**Scientific Justification** *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

The local environment in galaxy clusters is known to influence the star formation rates (SFR) of galaxies in them (e.g. Butcher & Oemler, 1984). Multiple mechanisms have been proposed to explain the difference in star formation between more isolated galaxies and the dense regions of clusters that depend on local mass environment (e.g. Moore 1999, Ghigna 2000). One limiting factor in the understanding of environmental influences on star formation is the lack of observations that measure star formation at low rates for faint cluster members.

Recent studies have been very successful in measuring the SFR of faint galaxies using narrow band filters to capture H$\alpha$ emission in clusters (Shioya 2008, Tadaki 2010). For clusters, where the redshift range of galaxies is small, narrow-band imaging is a more efficient way of measuring the SFR than multi-object spectroscopy because it captures the star formation of (almost) all of the cluster members at once. However, contamination from unrelated emission lines from background galaxies can be quite important, particularly as one probes the fainter cluster galaxy population.

We propose to use narrow-band imaging of H$\alpha$ and O[II] emission from star forming galaxies in three clusters at $z = 0.25$: Abell 1835, a very well studied cluster, and two similar mass clusters, Abell 2070 and 0992. We will be sensitive to SFR as low as 0.2 solar masses/year from H$\alpha$ emission for galaxies as faint as $i_{AB} = 24.0$.

Near $z = 0.25$, rest-frame H$\alpha$ ($\lambda = 656.3$ nm) and O[II] ($\lambda = 372.7$ nm) emissions are redshifted into the Rhoads 820R (Rhoads 2000) and WR CIII narrow band filters, respectively. Because only galaxies in a very narrow redshift range will have flux excess in both the Rhoads 820R and WR CIII filters, requiring detection in both narrow bands drastically reduces the contamination from other emission lines and allows for clean determinations of the total cluster SFR.

One of the potential perils of narrow band filters is the risk that the cluster galaxy peculiar velocities would shift the lines outside of the filter bandpasses. In figure 1, we show that, given a realistic LOS velocity distribution, 78% of galaxies in Abell 1835 and 2070, and 60% of galaxies in Abell 0992, will have lines that fall within the 50% of peak transmission limits of the filters. For these systems, we will be able to measure SFR with 30% error, with the dominant contribution coming from the unknown peculiar velocities of the galaxies, which results in the emission line being located at an unknown position under the transmission curve.

These observations will help to complete the picture of SFR as a function of location within Abell 1835, a cluster with existing x-ray and weak gravitational lensing observations. Using far infared fluxes from the Herschel satellite and spectroscopic methods, Pereira et al 2010 measured SFR in 45 cluster members in the range of 2 to 20 solar masses/year and mapped their spatial locations. By detecting H$\alpha$ and O[II] emission, we will confirm many additional faint and low SFR cluster members, extending the sensitivity limits by roughly an order of magnitude in SFR and more than a factor of 15 in galaxy flux. As a further check, our brighter star forming galaxies will be matched with the catalog of 630 spectroscopically confirmed Abell 1835 galaxies (with $R < 22$) from Czoske (2004).

In addition to measuring the SFR in Abell 1835, we will obtain narrow band imaging of Abell 2070 and Abell 0992. We will match the values of SFR from the narrow band H$\alpha$ measurements of this proposal to the values from Pereira et al 2010 on common galaxies in Abell 1835, obtaining a confirmation of the proposed narrow band SFR measurements and calibrating the SFR measurements in Abell 2070 and 0992. Although there is less existing data on the latter two clusters, X-ray and lensing measurements suggest they are similar in mass and richness to Abell 1835 (Hennawi 2008, White 1997).

**References**

Butcher H., Oemler A., 1984, ApJ 285, 426.

Czoske, O., in IAU Colloq. 195: Outskirts of Galaxy Clusters: Intense Life in the Suburbs, ed. A. Diaferio, 183187

Ghigna, S. et al., 2000, ApJ, 544, 616.

Hennawi, J. et al., 2008, AJ, 135, 664H.

Kennicutt, R., 1998, ARA&A, 36, 189-231.

Kodama, T., et al., 2004, MNRAS, 354, 1103.

Massey, P., et al., 1989, ApJ, 358, 344.

Moore, B. et al., 1999, ApJL, 524, L19-L22.

Neugent, K.F. & Massey, P., 2011, ApJ, 733, 123.

Pereira, M.J. et al., 2010, A&AL, 518, 40.

Rhoads, J. et al., 2000, ApJL 545, L85.

Shioya, Y. et al., 2008, ApJS, 175, 128S.

Tadaki, K. et al., 2010, arXiv:1012.4860.

White, D.A., et al., 1997, MNRAS, 292, 419.

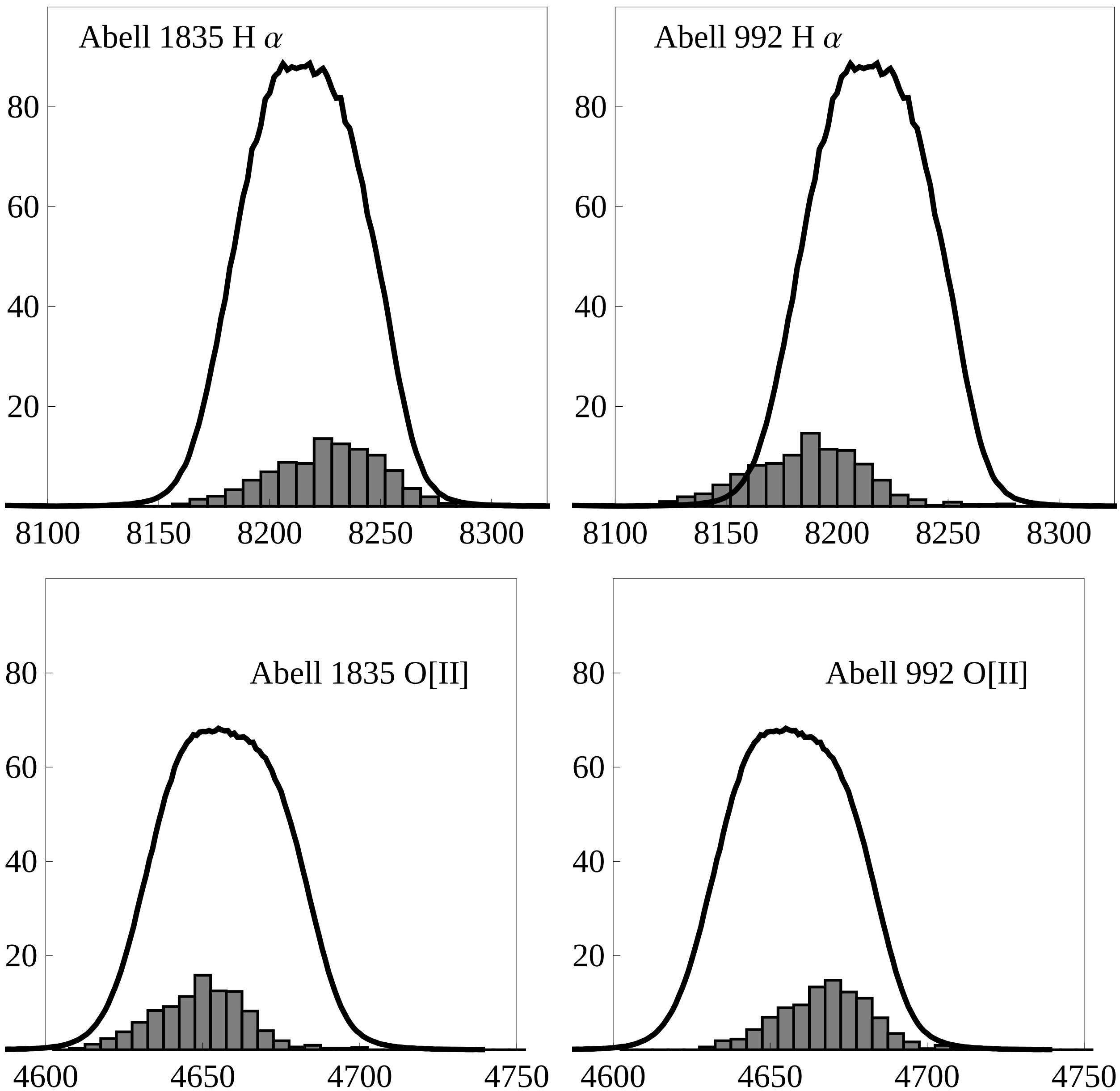


Figure 1: Transmission curves of the Rhoads 820R (k1047), top, and WR CIII (k1021), bottom, narrow band filters along with an estimate of the central wavelength distribution for emission of individual galaxies. The distribution is calculated using the actual redshift distribution observed for the Coma cluster galaxies, redshifted for our clusters (and corrected for the $1 + z$ expansion in measured line of sight dispersions). We define galaxies to be detectable if their systemic redshift would result in H$\alpha$ and O[II] emission within the 50% of peak transmission bounds for the k1047 and k1021 filters respectively (8181 to 8262 angstroms and 4631 to 4684 angstroms). For Abell 992, 501 of 840 (60%), and for Abell 1835 and 2070, 657 of 840 (78%), of the galaxies would be detected. This is a conservative estimate that does not take into account that Abell 1835 is less massive than Coma (so that its fastest galaxies will have lower velocities) or the width of the emission lines.

**Experimental Design** *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

We seek to measure the amount and distribution of star formation in cluster galaxies, particularly SFR in fainter cluster members that are difficult to successfully target at these redshifts with spectroscopic and infared methods. Our proposal derives estimates of the SFR from the H$\alpha$ flux in three clusters of similar mass and richness, testing for significant cluster-to-cluster variation in the faint galaxy SFR.

We will measure the H$\alpha$ emission in Abell 1835, Abell 0992, and Abell 2070 by measuring the narrow band flux excess in the Rhoads 820R filter, relative to Sloan $i$. The Rhoads 820R filter, designed to take advantage of a window with minimal sky emission lines, is ideally suited to measuring the H$\alpha$ emission of clusters with $z = 0.25$. At the prime focus of the Mayall, the filter transmits with minimal loss in a central $30'$ diameter region, corresponding to 7 Mpc at the cluster redshift. This extends beyond the entire virial region of the cluster in a single Mosaic pointing, reaching the region where star formation is expected to be higher.

With the red-sensitive E2V chips of the Mosaic 1.1 imager, we can measure star formation rates for galaxies as low as SFR= 0.2 solar masses/year, corresponding to an equivalent width of 23Å (for galaxies as faint as $i_{AB} = 24.0$) in 1.5 hours of observation in the Rhoads 820R. Our proposal extends the knowledge of star formation to galaxies with rates one order of magnitude lower than current limits and to galaxies more than two magnitudes fainter than have previously been studied at this redshift. Thus, we can quantitatively compare the SFR of faint cluster galaxies at z=0.25 to measurements made in nearby clusters, testing the rate of evolution in the SFR and its spatial distribution within the clusters.

In addition to measuring H$\alpha$ in the Rhoads 820R filter, we will measure O[II] emission flux excess in the WR CIII filter relative to Sloan $g$. Because variations in the amplitude of the 4000Å break and extinction complicate estimates of SFR from the O[II] emission, the SFR will be calculated from the H$\alpha$ flux. The O[II] emission will be used only as a "background veto" to eliminate contamination from emission line galaxies at other redshifts, solving one of the fundamental difficulties in deriving SFR from narrow band imaging. Although we will only require S/N=3 detection of the flux in WR CIII, due to the extinction and difference in filter and detector transmission, we will require 5 hours of exposure per cluster.

To isolate the line emission, Sloan $g$ and $i$ images $\sim$ 1 magnitude deeper than the corresponding narrow-band imaging are required to ensure that photometry errors in the broad band imaging do not dominate the error in the narrow band emission calculations.

The H$\alpha$ flux will be contaminated by weak N[II] $\lambda\lambda 6548,\ 6583$ lines. We will utilize the standard approximate fraction of contamination to correct for this. After correcting for $\sim$ 1 magnitude extinction in both the broad and narrow bands, the combined H$\alpha$ and N[II] flux will be measured as in Equation 1 in Tadaki et al 2010, and after converting $F_{H\alpha+[NII]}$ to a luminosity, the N[II] contribution will be removed and a SFR will be calculated from the Kennicutt (1998) relations.

Because we do not know the peculiar velocities of the cluster galaxies from our measurements, our measured SFR of individual galaxies will be uncertain, and we will miss some galaxies. However, knowing the systemic redshift and the velocity dispersion, we will be able to estimate the mean SFR for the cluster and for cluster populations as a function of galaxy luminosity with an uncertainty smaller than that of the Kennicutt (1998) relations.

**Proprietary Period:** 18 months

**Use of Other Facilities or Resources** *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

This proposal makes use of SDSS imaging in the cluster fields for photometric calibration of the broadband images.

Ultimately, our goal is to study how the faint galaxy star formation is affected by the local mass environment. Although the observations proposed here will measure the star formation rate with high accuracy, the local mass environment will not be measured (for instance, from gravitational lensing). In the case of Abell 1835, existing Subaru weak lensing data already provides a basic mass map, and existing Herschel and spectroscopic observations provide SFR in 45 cluster galaxies that we will use for calibration. We will be proposing to obtain observations for weak lensing reconstructions of the central regions of all three clusters, and wide-field weak lensing measurements of Abell 2070 and 0992 with WIYN or MMT.

Spatial variation of the of the AGN fraction poses a potential complication to the interpretation of the data. We will propose to obtain Chandra or XMM data of the one cluster with no high-resolution X-ray observations (Abell 2070), as well as potentially deeper observations of Abell 0992. Existing X-ray observations of Abell 1835 will be used to exclude AGN in this system. An existing spectroscopic catalog of cluster members of Abell 1835 to $R = 22$ will be used to confirm the star formation estimates and limits on the brighter cluster members (Czoske 2004).

The PI has an affiliate appointment at Brown University and has access to all the computational and data analysis resources there. co-I Dell'Antonio has adequate computational resources for the analysis. co-I Huwe will assist with the data reduction and galaxy identification. Publication costs will be supported by the Brown Physics Department's publications fund.

**Previous Use of NOAO Facilities** *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

The PI has not had any telescope time allocations during the past two years.

## Observing Run Details for Run 1: KP-4m/MOSA

**Technical Description** *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

The wide field of view, efficient Mosaic 1.1 E2V CCDS and a combination of two narrow band filters that capture H$\alpha$ and O[II] emission make the Mayall 4m telescope well suited to studying star formation in faint galaxies.

Rhoads et al (2000) obtained 5$\sigma$ detections (with a 2.5$''$ aperture) in the Rhoads 820nm (k1047) filter at $\sim$ 24.7 AB magnitude in 9 hours of integration with the Mayall 4-m and the Mosaic 1 CCDs. We require S/N$>$ 10 detections (so that the SFR errors are not dominated by the photometry) of galaxies with AB mag=23 in the 820R filter. Scaling from the Rhoads result, we will obtain a 10$\sigma$ detection of 22.75 AB galaxies in 1 hour of integration, and $\sim$ 23 in 1.5 hours of integration. Some of our cluster galaxies will be larger than those detected by Rhoads et al (2000). However, the Mosaic 1.1 E2V CCDS are $\sim$ 30% more efficient at 820nm than the SiTE chips of Mosaic 1, compensating for the sensitivity loss due to source extension. We will divide our exposures into 10x600 second exposures (two standard mosdithers) to completely cover the cluster while keeping the variation in exposure time across the field as uniform as possible.

The depth requirement in the WR CIII filter is complicated by significant line emission extinction. Even though we do not use the rest-frame O[II] emission to measure star formation, it is still important to detect emission to confirm that the galaxy is at the cluster redshift. Using the WR CIII filter to search for Wolf-Rayet stars in M33, Neugent & Massey 2011 obtained $> 5\sigma$ detections of stars to AB=21 in 900 s total exposures. Because we only need to demonstrate consistency, we aim for 3$\sigma$ detection of the line excess. Assuming 1.5 magnitudes of internal extinction, the Kennicutt (1998) relations suggest that a galaxy with $g = 24$ and a SFR = 0.2 solar masses per year would have a typical magnitude in WR CIII of 23.7. Scaling from the Neugent & Massey results, we will reach a 3$\sigma$ detection for the flux excess in 4.8 hours. We will obtain 15x1200s exposures in the WR CIII filter (3 mosdither patterns).

To compute flux excesses, we need $i$ and $g$ band imaging slightly deeper than the narrow band images. Using the NOAO imaging ETC, we estimate needing only 820 s in $i$ and 700 s in $g$, though we will take 5x200 s exposures in both broad band filters to help with making sky flats. We will use the standard mosdither pattern to fill the gaps and to move cluster galaxies off each other to make a sky flat for the broad-band filters. We will probably not have sufficient signal in the narrow-band filters to effectively use night sky flats.

The total exposure time per cluster is 26,000 seconds, in 35 exposures. Because of the fast readout time of the Mosaic 1.1, the overhead is less than 1200 seconds. There will be overhead associated with slews between the three clusters and to allow the mirror pressure support to adjust, so we allot 1 hour to overhead per cluster. Each cluster will take 8.2 hours of actual time to observe.

We will obtain standard star images of our fields for broad-band calibration if the nights are photometric, although as a backup we note that all our fields overlap the SDSS DR7 footprint, so we can normalize our magnitudes to the SDSS. We will calibrate the narrow band filters by requiring that the mean (narrow-broad) color be zero for unsaturated stars in the field (see Kodama 2004). We will also obtain images of spectrophotometric standards (Massey 1989) to ensure the calibrations are consistent with standard star zero points. Standard star observations will consume up to 40 minutes per night, or 2 extra hours. Added to the 8 hours per cluster, we can observe all three clusters in 3 grey nights.

## Instrument Configuration

| | | |
|---|---|---|
| Filters: g,i,820R (k1047),WRCIII (k1021) | Slit: | Fiber cable: |
| Grating/grism: | Multislit: no | Corrector: |
| Order: | $\lambda_{start}$: | Collimator: |
| Cross disperser: | $\lambda_{end}$: | Atmos. disp. corr.: yes |

**R.A. range of principal targets (hours):** 10 to 16

**Dec. range of principal targets (degrees):** 2 to 35

**Special Instrument Requirements** *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.16.