Kinematics and star formation histories of brightest cluster galaxies

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Abstract. We present a study on the kinematics and star formation histories of brightest cluster galaxies (BCGs) in a sample of clusters over a 3.4 Gyr time period (0.3 $< z <$ 0.8). We analyze the spectroscopic data of Brightest cluster galaxies Evolution with AdvACT, MeerKAT and SALT (BEAMS) BCGs observed on the Southern African Large Telescope (SALT). We focus on stacking the clusters as a function of redshift, to increase the signal-to-noise ratios. We fit the stacked BCG spectra using full-spectrum fitting to measure kinematics and stellar populations, from which star formation histories can be inferred. For the example stack that we present here it is found to have ages in the range 2.74 - 9.12 Gyr, and metallicities in the range -1.17 $<$ [Z/H] $<$ 0.06 depending on the model used. The spectra also indicates the presence of a younger component although with varying contribution, depending on the model used. The results are highly dependent on the stellar models and libraries chosen, emphasising the need to fit multiple models and interpret their difference.

1. Introduction

Brightest cluster galaxies (BCGs) are the most massive and luminous galaxies in the Universe. A typical BCG is located near the centre of its parent cluster and well-aligned with the cluster galaxy distribution suggesting that it lies at the bottom of the cluster's gravitational potential well [4, 9]. Their origin and evolution is intimately linked with the evolution of their host cluster, and therefore can provide direct information on the formation and history of large-scale structures in the Universe.

BCGs Evolution with AdvACT, MeerKAT and SALT (BEAMS)[1] is a new spectroscopic survey of BCGs in massive clusters detected by the Advanced Atacama Cosmology Telescope (AdvACT). The goal is to trace the evolution of Active galactic nucleus (AGN)

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[1] BEAMS - https://acru.ukzn.ac.za/~beams/

feedback (both radio and quasar mode), stellar populations, and the growth of central galaxies in clusters over a 3.4 Gyr time period ($0.3 < z < 0.8$). The clusters are detected using the redshift-independent Sunyaev-Zel'dovich (SZ) effect [13, 14], and the targets are selected from within the Dark Energy Survey (DES) [12] footprint which ensures excellent quality deep imaging.

A fraction of the BCGs exhibit recent star formation and therefore have evolutionary histories that are in stark contrast with the conventional expectation that giant elliptical galaxies in the cluster environment are all quiescent, passively evolving, 'red and dead' systems [2, 8]. We are particularly interested in the star formation histories of the BCGs, and we investigate full-spectrum fitting to derive the stellar populations, first on single BCG spectra, and then on BCG spectra stacked in redshift bins. Here we describe some preliminary results from the BEAMS project.

2. Optical spectroscopy and data reduction

2.1. The cluster sample

The AdvACT SZ cluster survey is a sample of > 4000 optically confirmed clusters with both spectroscopic and photometric redshifts [6, 7]. The data in this study utilise a large sample of BEAMS optical selected clusters, with a well-defined selection function that is relatively independent of cluster mass across a wide range of redshifts. The following selection criteria were used to select a sample of clusters to be observed with SALT (2019-1-LSP-001, PI: Matt Hilton):

(i) firstly, a signal-to-noise ratio (S/N) $> 5\sigma$ cut was made in the AdvACT SZ detection significance;

(ii) restricted the redshift range to $0.3 < z < 0.8$;

(iii) the clusters are required to be within the footprint of DES.

Of the 186 clusters satisfying these criteria, 89 of them have been observed on the Robert Stobie Spectrograph (RSS) using the longslit spectroscopy mode over a period of three observing semesters.

2.2. Data reduction and the BCG slit

The data reduction was performed with the RSSMOSPipeline[2] [6], including wavelength calibration, and extraction of one dimensional (1D) spectra. The slit was positioned to observe more than one galaxy, and we needed to identify which of the extracted 1D spectra contained the BCG. The identification of the BCG slit was made via a visual inspection of the DES imaging with the aid of finder charts and region files. In Figure 1 given as an example, the long-slit data contains spectra for four galaxies. The BCG is located at the centre of the finder's chart where the green vertical and horizontal lines meet (see Fig. 1b), overlaying the region file on the DES imaging allowed us to approximate the slit that had the BCG. The BCG given in this example corresponds to the 1D spectra marked "slit 2". This process was repeated for all clusters in the survey.

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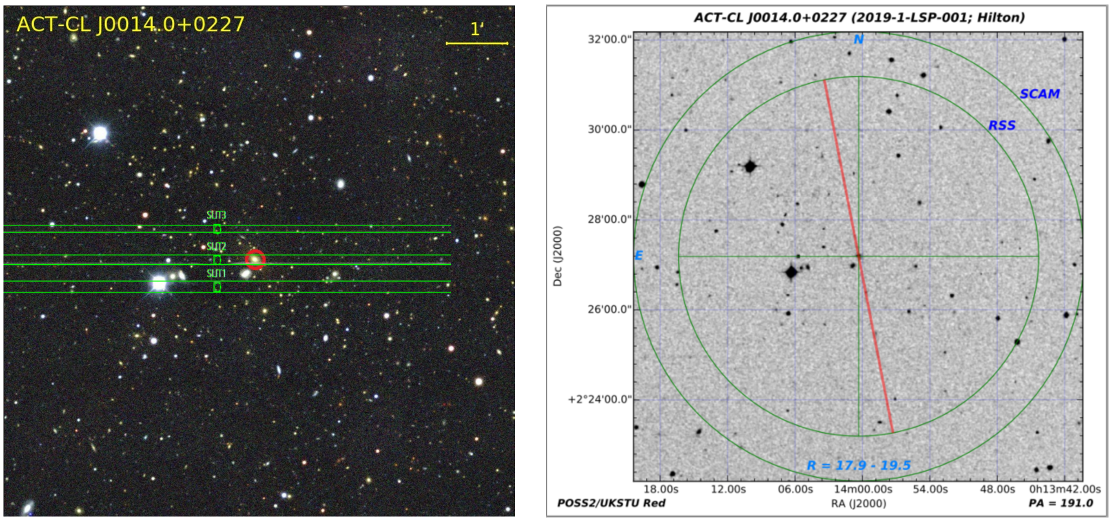
[2] `https://github.com/mattyowl/RSSMOSPipeline`



(a) (b)

Figure 1: (a) DES cluster image of ACT-CL J0014.0+0227 ($z = 0.337$). The BCG is circled in red. (b) SALT finder chart of J0014.0+0227, used in the identification process of the BCG. The green slit lines (not shown to scale) is the region file of J0014.0+0227, used in the identification process of the slit in which the BCG is located. The BCG is this scenario was in slit 2.

3. Spectral analysis

We used Penalized Pixel-Fitting (PPXF)[3] [1, 16] to find the stellar kinematics (velocity, V, and line-of-sight velocity dispersion, σ) and to measure any emission lines present. We first attempted to fit model spectra to the spectra of individual BCGs. In Figure 2, we can see that the S/N is too low, as PPXF struggled to fit the model spectra and the kinematics measured were not accurate. We used χ^2 statistics to determine the best fitting template.

In order to make improvements in the fit to the model spectra and to make accurate measurements of kinematic properties we stacked the spectra of BCGs of similar redshifts (see Figure 3), using *SPECSTACK*[4] [15]. The BCGs were firstly grouped into five groups, these were $0.3 \leq z < 0.4$, $0.4 \leq z < 0.5$, $0.5 \leq z < 0.6$, $0.6 \leq z < 0.7$ and $0.7 \leq z < 0.8$ and from these groups so-called "stacking groups" were derived by taking BCGs with redshift at ±0.05 of each other. The stacked spectra varied from 3 spectra to as much as 7 spectra per stacking group. From using *SPECSTACK* we can observe that the model fit to the spectra is much improved (see Figure 4), and thus the various measurements can be made more accurately, such as the velocity dispersion.

We use Fitting iteratively for relative likelihood analysis (FIREFLY)[5] [3, 5, 10, 11, 17] to fit the stacked spectra in order to derive the stellar population properties of BCGs (i.e.,

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[3] `https://www-astro.physics.ox.ac.uk/~mxc/software/`
[4] `https://specstack.readthedocs.io/en/latest/`
[5] `https://www.icg.port.ac.uk/firefly/`

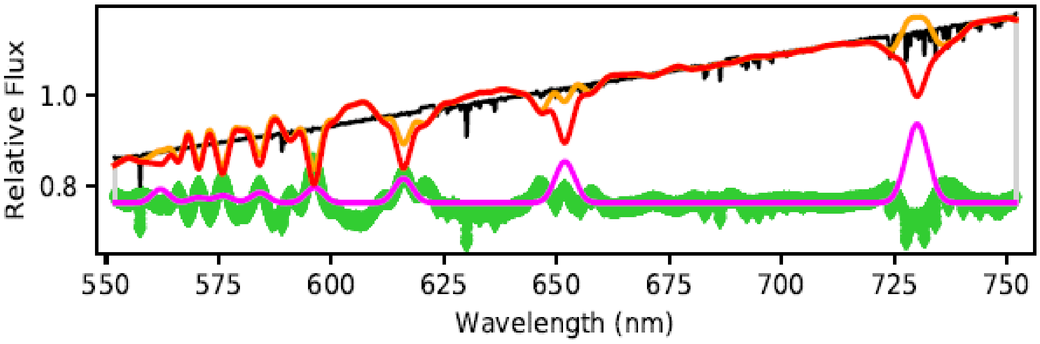


Figure 2: Spectra of ACT-CL J0014.0+0227 at z = 0.337, before stacking. The S/N of a single BCG is too low to fit with stellar templates. The black line is the relative flux of the observed spectrum. The red line is the pPXF fit for the stellar component, while the orange line is a fit to the gas emission lines The green symbols at the bottom are the fit residuals, while the blue lines is the gas only best-fitting spectrum.

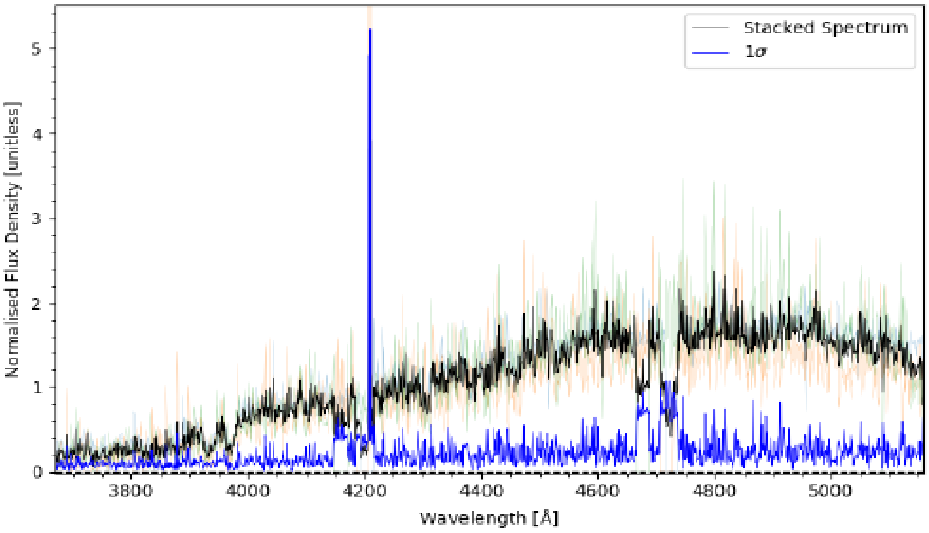


Figure 3: Stacked spectra of ACT-CL J0257.7-2209, ACT-CL J0405.9-4915 and ACT-CL J0014.0+0227 at z = 0.323, 0.325 and 0.337. The black line represents the stacked spectra. Green, orange and cyan are the three individual spectra that were stacked together. The blue line at the bottom is the residual.

age, metallicity and dust extinction).

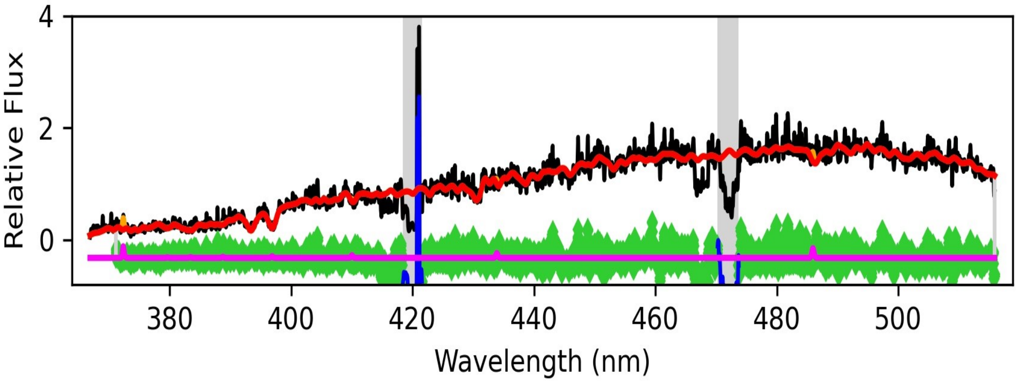
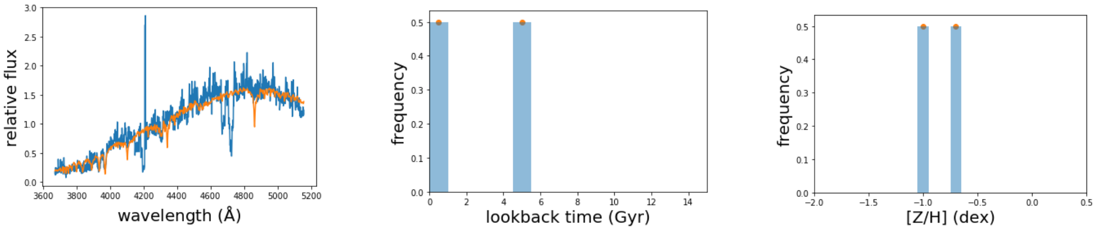


Figure 4: Stacked spectra model fit. The grey lines represent the masked regions of the "SALT chip gaps" in order to improve the model fit of the spectra. The red line is the pPXF fit for the stellar component, while the orange line is a fit to the gas emission lines The green symbols at the bottom are the fit residuals, while the blue lines is the gas only best-fitting spectrum.

4. Results

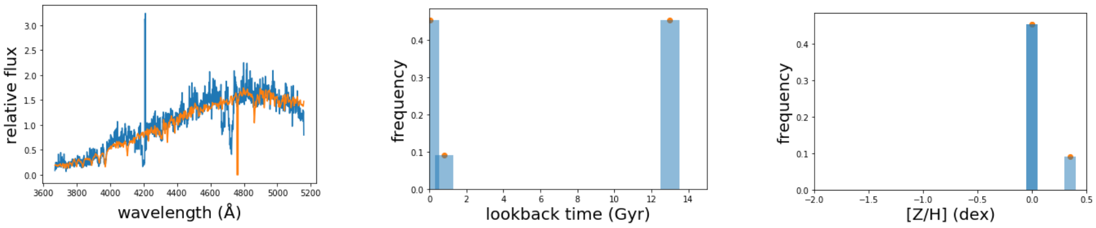
We show preliminary results from the FIREFLY analysis of the stacked spectra of ACT-CL J0257.7-2209, ACT-CL J0405.9-4915 and ACT-CL J0014.0+0227 as an example. We fit different libraries, i.e., the MaStar library [11] and the M11 library [10] together with different initial mass functions (IMFs). This is done to quantify the systematic uncertainties on the ages and metallicities measured using different stellar population model ingredients. The M11 library contains the MILES and STELIB models. The MILES model has spectra of 985 stars with a wavelength range of 3500 - 7430 Å covering most evolutionary stages based upon what can be expected to exist in our Galaxy at all metallicities down to [Fe/H] $\sim$ -2.0 [10]. The STELIB model has spectra of 249 stars with a wavelength range of 3200 - 9300 Å, most spectral types and luminosity classes are included, with a fair coverage in metallicity. The MaStar library comprises of $\sim$ 9000, high S/N spectra, and has the E-MaStar and Th-MaStar models both models have a wavelength range of 3621.6 - 10352.3 Å[11].

We show for example the results from the E-MaStar model (see Figure 5) given here for the Kroupa (KR) IMF, STELIB model (see Figure 6) given here for both the KR and Salpeter (SS) IMFs and the MILES model (see Figure 7) given here for the KR IMF. For the STELIB model both IMFs show that the stacked spectra has an average age of 6.02 Gyrs and a metallicity of 0.05 dex. The MILES model for the SS IMF showed an age of 9.08 Gyrs and a metallicity of -1.08 dex and for the KR IMF an age of 9.12 Gyrs and metallicity of -1.01 dex. The E-MaStar produced an age of 3.82 Gyrs and a metallicity of -1.16 dex for the SS IMF and for the KR IMF an age of 2.74 Gyrs and a metallicity of -0.82 dex.



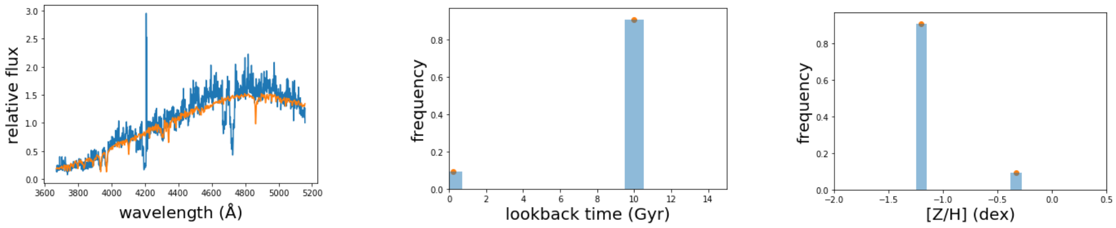
(a) (b) (c)

Figure 5: E-MaStar model. (a) The fitted spectra (b) Lookback time (age) (c) and the metallicity of the stacked spectra. The orange line represents the FIREFLY best fit. In (b) it can be seen that this stacked spectrum can be fitted by two stellar components (a young ∼5 Gyr component, and a much younger stellar component).



(a) (b) (c)

Figure 6: STELIB Model (a) The fitted spectra, (b) Lookback time (age) (c) and the metallicity of the stacked spectra. The orange line represents the FIREFLY best fit. In (b) it can be seen that this stacked spectrum can be fitted by three stellar components (an old ∼13 Gyr component, a bigger and much young stellar component and a much smaller younger stellar component).



(a) (b) (c)

Figure 7: MILES model (a) The fitted spectra, (b) Lookback time (age) (c) and the metallicity of the stacked spectra. The orange line represents the FIREFLY best fit. In (b) it can be seen that this stacked spectrum can be fitted by two stellar components (an old 10 Gyr component, and a much smaller, younger stellar component).

5. Conclusions

We investigate the kinematics and star formation histories in BCGs drawn from the Advanced Atacama Cosmology Telescope (AdvACT) Sunyaev–Zel'dovich (SZ) cluster survey at redshift $0.3 < z < 0.8$. From the preliminary results, we observe that single BCG spectrum does not have enough S/N to fit with spectral fitting software (i.e., PPXF and FIREFLY) as the fit fails. We use *SPECSTACK* to stack spectra in redshift bins to achieve enough S/N. We measure stellar kinematics with PPXF. We measure stellar populations using FIREFLY for different models, stellar libraries and IMFs to determine the ages and metallicies of the stacked spectra (and systematic errors). For the example stack that we present here we find that the MILES model is a poorer fit compared to the other two based on the continuum level. The STELIB and E-MaStar models both give 'intermediate' age stellar components and indicate the presence of a younger component (although with varying contributions). The results are highly dependent on the stellar models and libraries chosen, emphasising the need to fit multiple models and interpret their differences. Stacking spectra enables us to investigate BCG evolution with redshift.

6. Acknowledgements

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