SALT spectroscopy to measure the abundances of gas-rich galaxies in Fornax A

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Abstract. The Fornax cluster is currently undergoing mass assembly. It has a lower-density group surrounding the radio galaxy NGC1316 (Fornax A) currently falling into the cluster. Infalling groups are ideal environments to study the transformation in the properties of the multi-phase gas due to e.g. tidal interactions and ram pressure stripping due to the velocity change at the boundary between the group and cluster. We have optical and Hα imaging of Fornax A, and also obtained MeerKAT data, which for the first time resolved HI emission in different substructures in the subgroup, often coinciding with detections in Hα. We then obtained spectroscopy of 11 gas-rich galaxies on SALT (Southern African Large Telescope). In this study, a combination of spectral fitting routines are used to accurately separate stellar continuum and absorption lines from the ionized gas emission in the observed SALT spectra, and to measure gas as well as stellar population properties. We present our latest results from the SALT spectral analysis, which will ultimately be combined with the information obtained from the various other multi-wavelength observations to fully understand the physical processes and the multi-phase gas. We illustrate our methodology by presenting results for NGC 1310 as an example. Our preliminary measurements of the gas abundances in NGC 1310 suggest that warm gas is photo-ionised by star formation.

1. Introduction

The Fornax cluster, the nearest massive cluster in the Southern sky, is actively assembling mass which makes it an ideal laboratory for studying the evolution of galaxy clusters, the physics of gas accretion and stripping of infalling galaxies, and the connection between these processes and the neutral medium in the cosmic web. Numerous observational campaigns have focused on the Fornax cluster; these include the deep optical imaging from the Fornax Deep Survey (FDS; [1]), optical integral field unit observations of selected targets [2, 3], the Atacama Large Millimeter Array (ALMA) observations of the cold molecular gas [4, 5], far-infrared Hershel imaging [6], and HI surveys with MeerKAT [7]. Studying the physical processes that drive the evolution of galaxies in galaxy clusters will help in answering questions as; how do these galaxies lose their cold gas, and why they stop accreting new gas? To answer these questions, we need optical spectroscopy to study the composition and kinematics of the warm ionised gas, in addition to the other wavelength observations. Figure 1 shows the HI velocity field from [8] where the known galaxies and previously detected clouds and tails in the Intragroup Medium (IGM) have been labeled. We can combine our SALT spectroscopy with previous studies, e.g. the study by [8] to investigate the pre-processing and HI morphology, including the gas (atomic and molecular) scaling relations in the Fornax A group. Studies from several observational campaigns will also provide an understanding of the processes of gas accretion or removal.

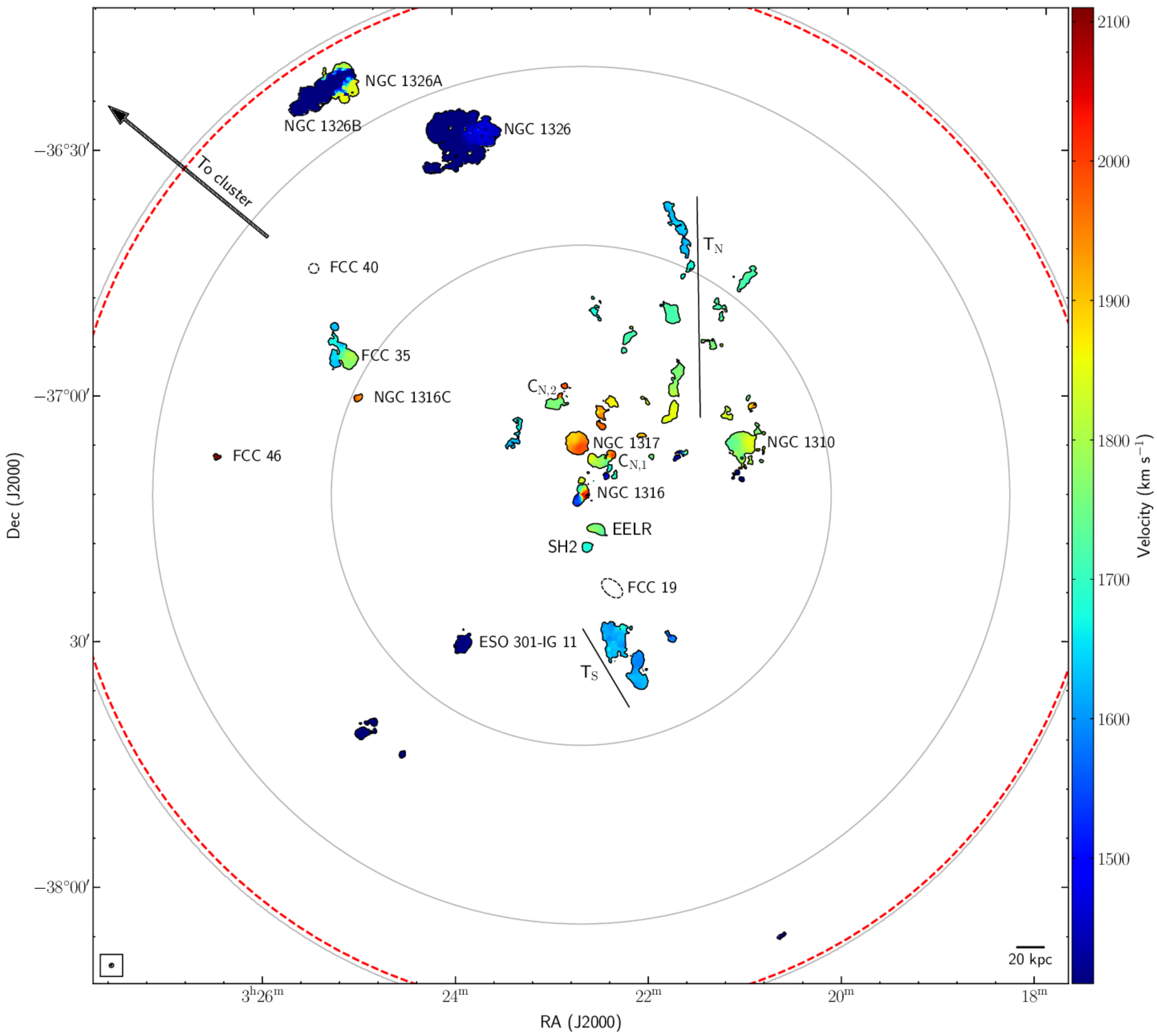

Figure 1. The HI velocity field of Fornax A from [8] showing the known galaxies and previously detected clouds and tails (T_N and T_S denotes the Northern and Southern tails respectively). The grey circles represent the sensitivity of the primary beam at 50, 20 and 2%. The red dashed circle indicates the 0.38 Mpc virial radius of the group.

2. Observations and Data Reduction

The 11 galaxies in the Fornax A group were observed with the South African Large Telescope (SALT) during November and December 2019 with more observations allocated for the remainder of 2021 (SALT Proposal ID: 2019-2-MLT-002 and 2020-2-SCI-029, PI: Ilani Loubser). To measure the strong emission lines of interest, the PG1300 grating was used at an angle of 44.5° which corresponds to a spatial scale of 0.127" and a spatial resolution of 0.33 $\AA$.

A series of reduction steps were carried out to reduce and analyze the SALT spectral data. First, a cosmic ray correction was applied to clean the images of bad pixels and cosmic rays. Interpolation was then applied to the images to mask the chip gaps. Wavelength calibration, which includes identifying emission lines in the arc lamp spectrum and taking the wavelength solution and performing it up and down across the 2D spectrum was performed. The final 2D wavelength solution that will be applied to the actual science image was created. Figure 2 shows the 2D spectrum of NGC 1310 after interpolation and wavelength calibration. Background subtraction was done to remove skylines and any residual sky background flux followed by generating a variance image from the combined science images. Next, an extinction correction and primary aperture extraction was done and finally, flux calibration using a spectrophotometric standard star was be performed to get a calibrated spectrum. All the data reduction steps was carried with the Image Reduction and Analysis Facility[1] (IRAF; [9, 10, 18] and Pyraf (a Python-based alternative to IRAF)).

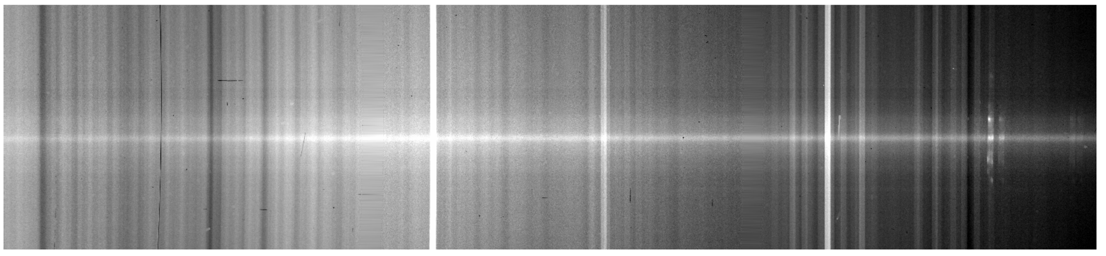

Figure 2. A 2D spectrum of NGC1310 after interpolation and wavelength calibration.

A combination of fitting routines, pPFX (Penalized Pixel-Fitting; [11, 19]) and FIREFLY [12], are used to accurately separate stellar continuum and absorption lines from the ionized gas emission in the observed SALT spectra. FIREFLY[2] is a fitting code that derives stellar population properties of stellar systems, be these observed galaxy or star cluster spectra or model spectra for simulations. FIREFLY uses an iterative best-fitting approach controlled by the Bayesian Information Criterion to fit combinations of single-burst star population models to spectroscopic data. There are no priors applied; instead, all solutions inside a statistical group are retained with their arbitrary weight, thus allowing one to map out the effect of intrinsic spectral energy distribution (SED) degeneracies on stellar population parameters, including age, metallicity, and dust reddening [12]. The routine was applied on the reduced spectra while changing parameters such as the Initial Mass Function (IMF; Kroupa [17] and Salpeter [13]) and models (M11 [16] and MaStar [15]). The equivalent age and metallicities, along with their uncertainties, were derived by calculating the average and standard deviation of the results.
The Python implementation of [11] freely accessible penalized Pixel Fitting (pPXF[3]) software, which includes the improvement described in [19], was used to derive stellar kinematics. After logarithmically rebinning the spectrum in the wavelength direction, the pPXF procedure recovers the line-of-sight velocity distribution (LOSVD) by fitting an optimized template to an observed galaxy spectrum directly in pixel space. By binning all spatial pixels within 5 arcseconds of the object's center, we first retrieved a high S/N spectrum for each galaxy. We calculated the best-fitting template spectrum, systemic velocity, and central velocity dispersion from these high S/N spectra. The higher-order Gauss-Hermite moments, h_3 and h_4, were also fitted.

[1] More information about the pipeline and installation can be found on https://iraf-community.github.io/.
[2] The code can be found from the dedicated Github repository https://github.com/FireflySpectra/firefly_release.
[3] See https://www-astro.physics.ox.ac.uk/~mxc/software/ for a full guide on installation and usage examples.

3. Results and Discussion

In this section, we present the preliminary results obtained from FIREFLY and pPXF for NGC 1310. Figure 3 represents the 1D spectrum of this galaxy where the Salpeter Initial Mass Function (IMF; [13]) was utilized. The black spectrum represents the model that best fit the data (as determined from minimising the Chi^2 residuals), which in this case was the STELIB model [14].

Figure 3. A 1D spectrum of NGC 1310 from FIREFLY for the extraction of star formation histories. The red spectrum represents the data with the black representing the fitted model which in this case is the STELIB model with the Salpeter IMF.

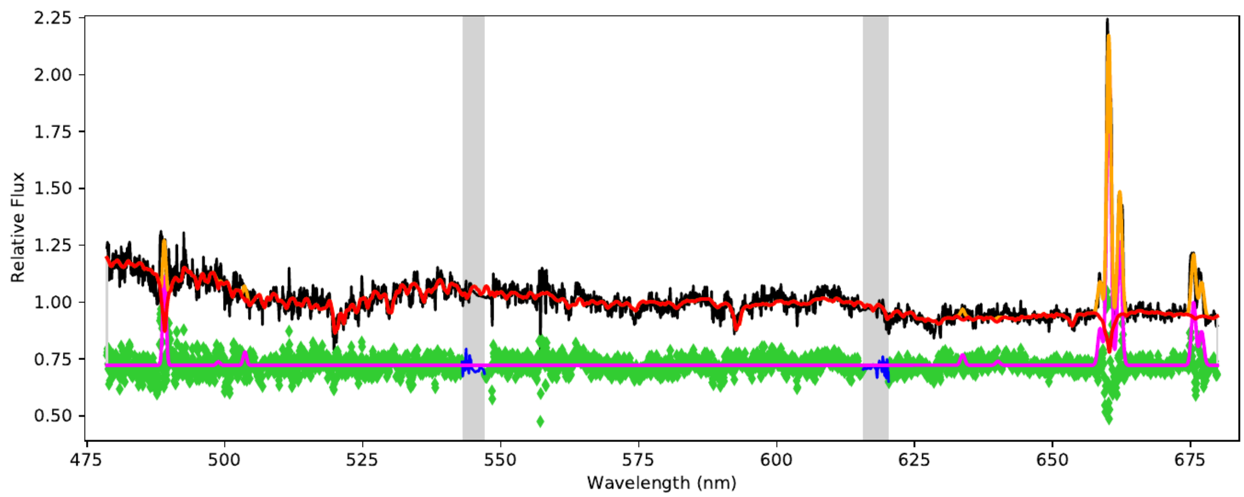

Figure 4. A 1D spectrum of NGC 1310 from pPXF where the grey regions indicate the masked chip gaps. The emission line ratios, e.g. Hα/[NII] is indicative of photo-ionisation by star formation.

Figure 4 also shows a 1D spectrum from pPXF where the Hα, [NII] and [SII] emission lines are clearly visible > 6500 Å. The grey regions indicate the masked chip gaps and 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.
The FIREFLY routine automatically fits multiple stellar populations (e.g. including a young stellar component in cases where the galaxy experienced a recent star formation episode). From the fitted model, we find that the galaxy has an approximate Single Stellar Population (SSP) equivalent age of 2.86 $\pm$ 0.55 Gyr, and a metallicity ([Z/H]) = -0.07 $\pm$ 0.03 dex. Since the dominant errors in stellar population analysis for high S/N spectra are systematic errors which stem from different stellar population model ingredients, we are currently repeating the analysis with various different stellar population models, e.g. MaStar [15] and M11 [16], for both a Kroupa [17] and a Salpeter IMF. This will allow us to determine the combination of stellar libraries and population models that are most consistent for this type of galaxy, and also allow us to quantify the systematic errors caused by using different stellar population models. This will consequently allow us to discard models that produce bad fits and inconsistent results. Once the FIREFLY analysis is complete, we will proceed to extract the stellar and gas kinematics from pPXF which will give us a clear picture of the star formation rates, kinematics and formation histories of the galaxies in our sample.

4. Conclusion

In this project we have displayed the techniques used in reducing SALT spectral data and explored the fitting routines applied to extract stellar properties of the observed galaxies. Our preliminary measurements of the gas abundances in NGC 1310 suggest that warm gas is photo-ionised by star formation.

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