PROCEEDINGS OF SCIENCE

Star Formation Histories of S0 Galaxies

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On the Hubble sequence of galaxies, S0s occupy a conspicious position - between elliptical and spiral galaxies - implying that all S0s are alike and a transition class of objects. However, using photometric analysis, in our past work [19, 20, 2, 4, 3, 5] we have shown that S0s represent a diverse variety of objects with different formation histories and mechanisms. As a part of this long term study of S0s and their overall place in galaxy formation theory, we are carrying out a detailed spectroscopic study of a select sample of S0 galaxies using SALT/RSS. This article describes the ongoing work, the challenges and proposed solutions.

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1. Introduction

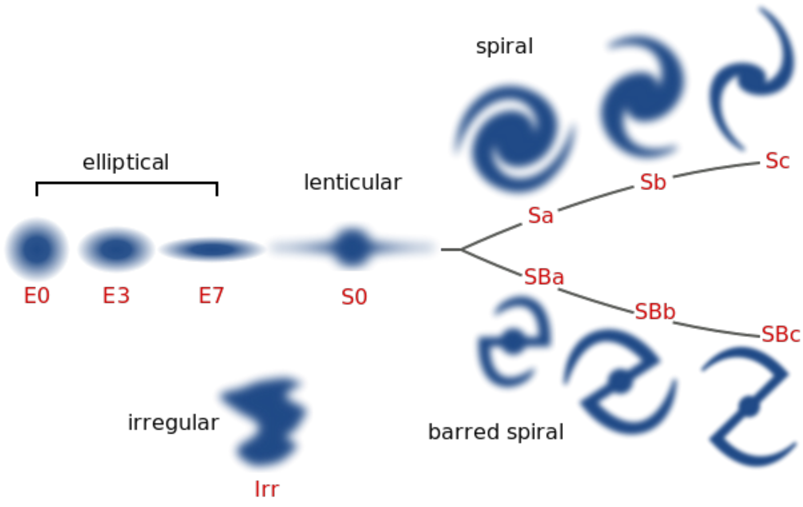

Figure 1: The Hubble tuning fork diagram of galaxy classification.

An important first step in the study of any class of objects in nature is to catalog them and come up with a preliminary classification scheme. When galaxies were discovered and it was slowly understood that as opposed to being nebulae within the Milky Way, they are actually 'island universes', i.e. other galaxies like the Milky Way, a classification scheme was introduced by Hubble [12]. This is the famous tuning fork diagram captured in Figure 1. At the junction of the tuning fork is a class called S0. The defining characteristic of these galaxies is the presence of a bulge and disk but with no obvious spiral arms. Other morphological features such as rings, bar, ovals etc. can be present. A large fraction of S0 galaxies contain a lens-like structure, hence they are also called lenticular galaxies.

Any classification scheme cannot be a random collection of objects - it has to capture the inter-relationships between the various subclasses and also capture the underlying Physics responsible for them. The placement of S0 galaxies at the junction of the tuning fork seems to suggest that they are a transition class. They could either be elliptical galaxies which somehow acquire a disk or a spiral galaxy which lost its arms in a process such as a ram pressure stripping. Early observational studies have shown this position seems justified as its properties such as amount of dust, gas fraction, star formation rate etc. are on average intermediate to those of ellipticals and spirals. Furthermore, that S0s occupy a single position implies that they are homologous.

Several studies carried out in the past decade have raised questions in relation to the understanding of S0s as summarized above. A typical approach adopted in many such studies involves studying and modelling the surface brightness distribution of these galaxies. By fitting suitable parametric models, one obtains quantitative descriptions of the galaxy morphology in the form of the best-fit parameters. The correlations between these parameters such as the Kormendy relation [15], the fundamental plane [10, 11], the photometric plane [13], the $r_e - r_d$ correlation [9] can be used to gain valuable insights into the processes governing the formation of galaxies. For example, the existence of a tight $r_e - r_d$ correlation, i.e. a correlation between bulge effective radius and disk scale length is often interpreted as support to formation scenarios where disks form first and grow bulges through various processes.

[2, 4, 3, 5] demonstrate that S0 galaxies appear not to obey many of the well known correlations between the structural parameters of the galaxies, when taken as a whole. However, when these galaxies are divided into two groups – bright and faint – based on a dividing luminosity of -24.5 on the K-band absolute magnitude scale – interesting trends emerge. Bright S0s are more like ellipticals and have likely formed in a similar manner, i.e. through rapid gas collapse at early epochs or hierarchical merging. Faint S0s, on the other hand, show signs of having formed secularly, i.e. through internal processes within the disk and are more likely to be related to spiral galaxies. [19, 20] use deep mid-infrared imaging obtained using the Infrared Array Camera on the Spitzer Space Telescope to verify the existence of pseudobulges [16] in S0 galaxies, with a greater likelihood to occur within the faint luminosity class. The authors also show that on average, the disk scale length of pseudobulges hosting S0s is lower than pseudobulges hosting spirals and use this finding to argue in favor of gas stripping of spirals as a mechanism of forming present day S0s.

Overall, it is clear that S0 galaxies are a collection of diverse objects, shaped by markedly different formation processes. The study described in this article aims at using SALT-RSS longslit spectroscopy to study the stellar populations within S0 galaxies in detail. This will help constrain various mechanisms proposed to explain these objects. Section 2 explains observations and an outline of the intended data analysis, Section 3 explains the challenges in performing the analysis and possible solutions and Section 4 offers a summary along with future prospects.

2. Observations and analysis

As explained in the previous section, the key goal of the current study is to use long slit spectra obtained using SALT/RSS to constrain formation histories of individual S0 galaxies. The sample used for this purpose is based on the Third Revised Catalog (RC3) of deVaucouleurs. All galaxies classified as S0s and having an integrated B-band magnitude brighter than 14.0 form the parent sample. From this parent sample, care has been taken to select S0 galaxies spanning a wide range of luminosities and morphological features such as bars, rings, classcical bulge hosts, pseudobulge hosts etc.

The method of analyzing stellar populations based on the spectra obtained from their integrated light is detailed in [6]. For convenience of the reader, a quick summary is presented here. One defines the most basic unit of stellar population known as the *Simple Stellar Population* (SSP) which is a group of stars born in a single burst in a gas cloud of a given metallicity. The distribution of masses in such a collection of stars is given by the Initial Mass Function (IMF). The IMF gives us the relative contribution of stars of various masses in this collection and the mass of each star in turn can be used to determine its spectrum as a function of age, using stellar evolution theory and spectral libraries. A weighted sum of all these spectra (weights being determined by the IMF) gives us the spectrum of the SSP as a function of age.

Once a scheme for handling the spectra of SSPs is in place, we can consider any given stellar population in a galaxy as a weighted sum of SSPs corrected for dust extinction, an overall redshift and broadening due to the random motion of stars in the galaxy. Such detailed modelling can be done using various tools such as Starlight [8], ULySS [14], NBursts [7] etc. In the current study we have chosen to model the spectrum using Starlight. The library of spectra chosen for constructing the spectrum of an SSP is the MILES library [17]. This code accepts a collection of SSPs of different ages and metallciities and returns a population vector which specifies the percentage contribution of the various SSPs to the galaxy spectrum,

The observations from SALT-RSS have been acquired by us through a series of proposals in the last few years. The proposals aimed at using the long-slit mode of the RSS with a PG0900 grating at 2×4 binning with a wavelength coverage between 3800 to 6800 Ångström. The targets have been selected to represent a population of S0s in the nearby Universe spanning a wide range of luminosities, morphological features and bulge types. A comparison sample of pseudobulge hosting spirals has also been observed. To do the basic reduction of the data, a custom pipeline was developed using Python and PyRAF. The pipeline is in the form of a collection of executable programs aimed at rearranging data headers, cosmic ray corrections, CCD gap filling, flat-fielding, wavelength calibration, coordinate transformation, background subtraction, relative flux calibration, foreground extinction correction and error frame construction. These tools can be made available to users of SALT as required. Having obtained the 2-d spectra, we now need a method of extracting spectra along different positions along the slit and model them.

3. Challenges and issues

3.1 High signal-to-noise across longslit

Any tool which models the entire spectrum has a basic requirement that the spectrum have a high signal-to-noise ratio (SNR). If the SNR is low, the recovered model is not reliable and is likely to be strongly affected by issues like the age-metallicity degeneracy. The galaxy is brightest at its centre and this brightness falls off as one moves away from the centre towards the outer regions. The convenient scheme of taking N rows in S steps and simply summing them up to produce a 1-d spectrum for a given position along the major axis results in a high SNR at the centre and a very poor one in the outer regions. This means that results are reliable only for the central regions of the galaxy and thus the study of variation of properties across the galaxy is not possible.

A method that circumvents this problem is to use a scheme where the number of rows being summed up to produce a 1-d spectrum for a given position is a function of the level of flux in that region of the long-slit. So, one would select just a few rows to sum up in regions of high brightness and as one moves to regions of lower brightness, the number of rows summed will be increased to achieve a high SNR spectrum. This is best illustrated in Figure 2 which shows the row number (spatial axis) on the X-axis and the intensity on the Y-axis. The coloured lines indicate the various aperture boundaries marked by our routine. As can be seen the apertures towards the centre of the spatial profile where the intensity is high are small – this means a lesser number of rows are being summed up. On the other hand, in the outer regions, a larger number of rows are being summed up in the outer regions to compensate for the lower flux, thus maintaining a high SNR.

Having solved the problem of maintaining SNR across the slit, we are faced with another issue – all inclined galaxies exhibit rotation which means that summing up the rows in a manner similar to summing up arrays would be equivalent of adding shifted spectra. This would 'mix' the spectra represented by each row. To prevent this, one needs to take into account the relative shifts due to the

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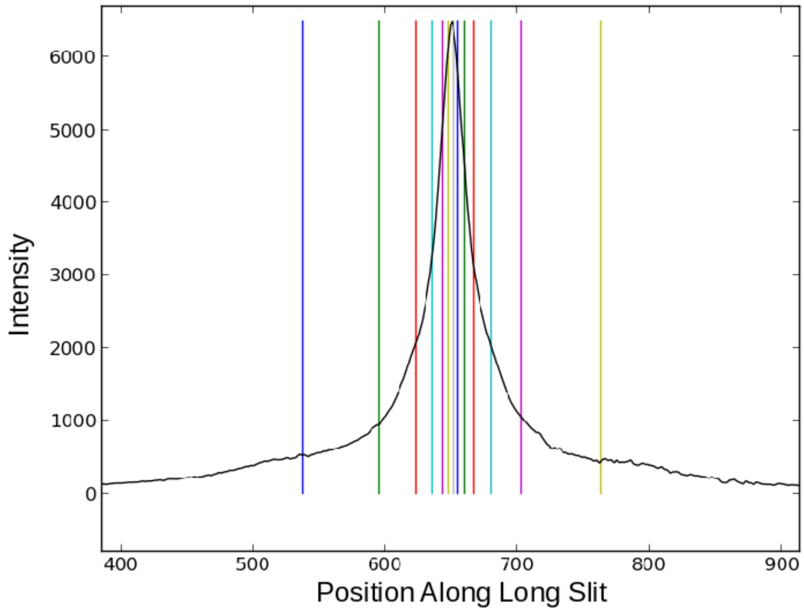

Figure 2: The intensity profile along the slit with a scheme of marking apertures to obtain high SNR 1d spectra from several points across the slit. The X-axis is the row number indicating the spatial direction of the long slit spectrum while Y-axis is flux in some scaled counts units. The various lines indicate boundaries of the final apertures to be summed up to produce a 1-d spectrum representative of that spatial position.

rotation of the galaxy before adding them up. This can be achieved by adding them in wavelength space by resampling the spectra on a common grid of wavelengths. Thus the complete approach involves determining the rotation curve, fitting it, using the best-fit function to model the relative shifts, resampling the spectra and then adding them up to produce a final 1-d spectrum.

3.2 Base selection

Starlight models the input spectrum as a linear combination of SSPs. The SSPs are selected by the user and input to Starlight. So naturally one is led to ask the question – what is the best method to choose these SSPs that constitute the base? Starlight comes equipped with a default base of 45 SSPs based on the stellar population libraries of [6]. This base comprises 15 spectra of different ages, each for three different metallicities. The spectra are hand picked and thus it is not guaranteed that they will prove to be adequate for representing a realistic spectrum through a suitable linear combination. A realistic galaxy will be a sum of SSPs picked from a continuum of ages and metallicities. A hand picked base does not assure a uniform sampling of the age and metallicity parameter space.

However, it is not feasible to model the galaxy spectrum using an infinite number of base spectra. Thus it seems reasonable to choose a large base with as much coverage of parameter space as possible. [1], for example, use a base of 150 spectra. But the computational overhead in the fitting process scales as N_*^2, i.e. as the square of the number of base spectra. Thus the computational time needed when such a large base is used will be very high. Also, many of the spectra of such a large base look sufficiently similar, i.e. there is an inherent degeneracy which makes the solutions unstable.

An ideal strategy, one which alleviates all these problems, is to devise a suitable method to automatically select base spectra for which degeneracies are minimum and the sampling of the parameters is as even as possible so as to mimic a smooth continuum. In order to do this, the prescription by [18] is followed. This method involves using the diffusion mapping a technique which is used for dimensionality reduction and which unlike techniques such as Principal Component Analysis (PCA) is a non-linear technique and thus suitable for spectra which clearly are non-linear functions of age, metallicity and other parameters. [18] have provided a MATLAB code which can accept base spectra containing any number of spectra of user's choosing and return a new set of spectra, lower in number but spanning uniformly the underlying parameters which govern the shape of these spectra. This way, we are able to reduce the number of base spectra but achieve a uniform coverage of the space of parameters that govern their shape.

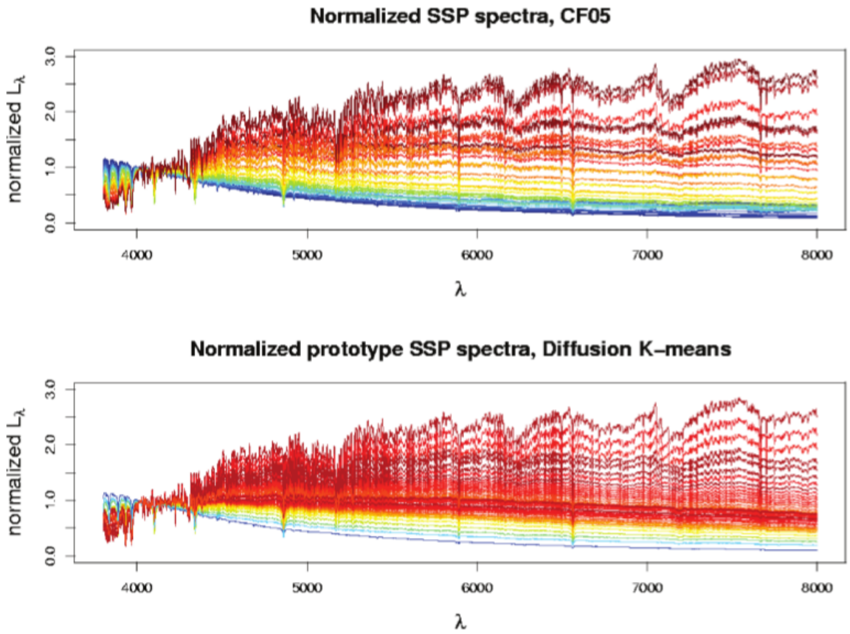

Figure 3: The top panel shows the spectra from the standard base of 45 spectra provided by [8] while the bottom panel shows the reconstructed base obtained from the algorithm of [18].

In the present study, we used the latest stellar libraries made available by MILES (Medium Resolution Isaac Newton Library of Empirical Spectra) to construct a large base of 150 spectra spanning three bins of metallicities with 50 age steps for each metallicity. These are then cast into a form compatible with the MATLAB code provided by [18] which is then executed to reduce the number of base spectra to 45. A base of 45 spectra is commonly accepted in literature as a compromise between having too many and too few base spectra. The effect of this technique of diffusion mapping is best illustrated using Figure 3. This shows spectra of various properties of a hand selected base in the top panel while the spectra reconstructed using this technique are shown in the bottom panel. This figure clearly shows the base spectra constructed using this algorithm offer a more uniform coverage and hence have lesser degeneracy. The authors also argue that this technique significantly reduces the *classic* age-metallicity degeneracy.

4. Summary and future

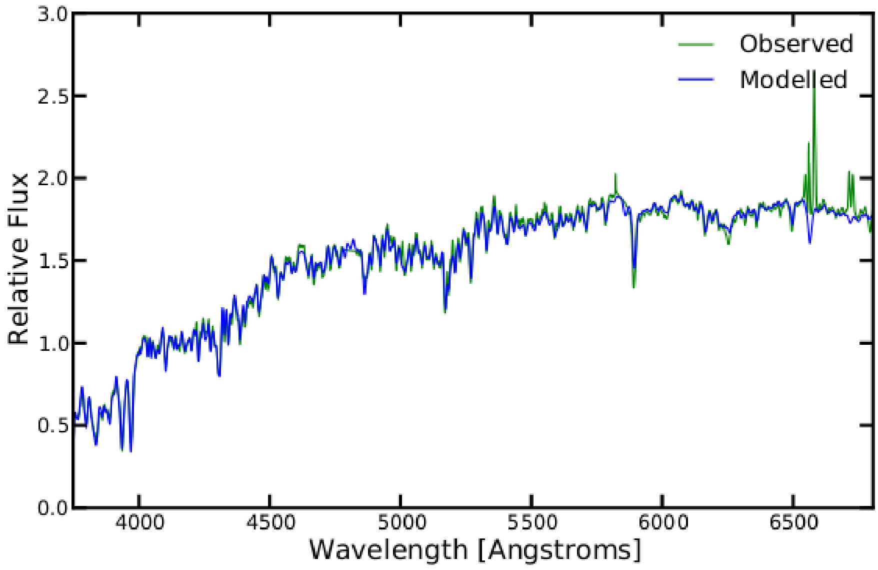

Figure 4: An example of a spectrum obtained using SALT-RSS for one of the galaxies in our sample and the best-fit Starlight model to it.

Using the techniques described in the previous section we have been able to successfully obtain very high SNR spectra and derive various parameters to describe the stellar populations for the galaxies in our sample. We have also been able to obtain age and metallicity gradients along the major axes of the galaxies in our sample. Figure 4 shows an example of a spectrum from the central region of one of the the galaxies in our sample. As can be seen, the quality of the spectrum obtained is very high and so is the fit obtained using Starlight.

At the time of writing this article, one of the sub-samples of S0s has been analyzed and we are in the process of preparing a manuscript discussing this analysis and its implications for the overall question of how S0 galaxies form.

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