

Optical Spectroscopy of Galaxies in the CLoGS and MHONGOOSE Surveys

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Abstract

The majority of observable galaxies within the local Universe can be found within group environments. Roughly at the centre of each galaxy group’s gravitational potential well lies each group’s brightest and most massive galaxy. The evolution of these galaxies is closely tied to their group environments, and recent studies have revealed that the dark matter content, hydrodynamics and baryonic processes of group environments are more intricate and diverse than previously thought. Therefore, the evolution of brightest group galaxies is more complex than previously expected. In this thesis, we study the spatially-resolved stellar kinematics and stellar populations of 18 brightest group early-type galaxies (BGEs) from the Complete Local-Volume Groups Sample (CLoGS). Spatially-resolved optical spectra have been obtained for these galaxies using the Southern African Large Telescope Robert Stobie Spectrograph (SALT RSS). The stellar kinematics and stellar populations of these galaxies are measured from their spectra using full-spectrum fitting software. Some of the CLoGS BGEs, such as NGC 128, NGC 4697, NGC 5084 and NGC 5153 are found to have marginal rotation, with an anisotropy parameter of $V_{max}/\sigma_0 \gtrsim 0.75$; however all of the CLoGS BGEs studied here are found to be pressure supported systems. We further find that the CLoGS BGEs have velocity dispersion slopes similar to field early-type galaxies in the central velocity dispersion range $2.1 \leq \log(\sigma_0) \leq 2.4$. The diversity of velocity dispersion slopes that we measure for the CLoGS BGEs, is not exactly reflected in the latest galaxy evolution simulations, suggesting that our understanding of the evolution of BGEs is still incomplete. We encourage the use of our spectroscopic results to further build and improve these galaxy evolution models. In line with recent multi-wavelength studies, we detect young stellar populations in some of the CLoGS BGEs, such as ESO 507-25, NGC 128 and NGC 7252. We further detect possibly old stellar populations for NGC 193, NGC 1550, and NGC 5044, known to have AGN activity and large-scale radio jets. We suggest that the AGN activity within these galaxies may have suppressed any new stars from forming. Additionally, we study the spatially-resolved stellar kinematics and stellar populations of HIPASS J1153-28, an HI-rich dwarf spiral galaxy from the MHONGOOSE survey. We demonstrate that the SALT RSS can provide complementary optical spectroscopic data for the ongoing MHONGOOSE survey, which can provide insight into how HI is processed within these galaxies.

Keywords: galaxies: groups: general; galaxies: evolution; galaxies: kinematics and dynamics; galaxies: stellar content; galaxies: star formation; techniques: imaging spectroscopy; techniques: radial velocities;

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Table of abbreviations

A table containing a list of abbreviations that will be used throughout text.

AGN	active galactic nuclei
BCG	brightest cluster galaxy
BGE	brightest group early-type galaxy
BGG	brightest group galaxy
CCD	charged coupled device
CLoGS	Complete Local-Volume Groups Sample
CSP	composite stellar population
ETG	early-type galaxy
FIREFLY	Fitting Iteratively for Likelihood Analysis
FITS	flexible image transfer system
FWHM	full-width half-maximum
HIPASS	HI Parkes All Sky Survey
IMF	initial mass function
LOSVD	line-of-sight-velocity-distribution
LGG	Lyons Groups of Galaxies
MHONGOOSE	MeerKAT HI Observations of Nearby Galactic Objects - Observing Southern Emitters
MILES	Medium-resolution INT Library of Emperical Spectra
NASA	National Aeronautics and Space Administration
NED	NASA Extragalactic Database
NGC	New General Catalog
pPXF	Penalised Pixel Fitting
RSS	Robert Stobie Spectrograph
SALT	Southern African Large Telescope
SFH	star formation history
SPS	stellar population synthesis
SSP	single stellar population
RSS	Robert Stobie Spectrograph

Chapter 1

Introduction and background

“What are galaxies? No one knew before 1900. Very few people knew in 1920. All astronomers knew after 1924.”

Allan Sandage

1.1 An Introduction to Galaxy Evolution

On December 30, 1924 in Washington, D.C., Edwin Hubble’s paper: “Cepheids in Spiral Nebulae” was read on his behalf to the American Astronomical Society (Berendzen and Hoskin, 1971). In Hubble’s paper, he announced his discovery of cepheid stars in the Andromeda nebula (M31) with the 100-inch Hooker Telescope at Mount Wilson Observatory (Berendzen and Hoskin, 1971). Hubble’s announcement was followed by three detailed papers on the cepheid stellar populations of M31 (Andromeda), M33, known today as the Triangulum galaxy, and NGC 6822, known today as Barnard’s galaxy (Sandage, 1961). The implications of these papers were clear, and the “island-Universe” concept, which states that galaxies are distributed throughout the Universe like “islands” with vast distances of space between them, had been proven (Berendzen and Hoskin, 1971). The way was now clear for astronomers to study the stellar populations of galaxies beyond our own and the field of extragalactic astronomy was born (Sandage, 1961).

Edwin Hubble went on to classify these galaxies in terms of their morphology (Hubble, 1982). Gérard de Vaucouleurs and Sidney van den Bergh later refined Hubble’s work on the classification of galaxies and the Hubble-De Vaucouleurs Diagram is still used to classify galaxies today, as summarised in section 1.1.1 (De Vaucouleurs, 1959; Van den Bergh, S., 1976; Sparke and Gallagher III, 2007).

With the significant development of both ground-based and space-based telescopes, astronomers have been able to resolve and study galaxies in much greater detail. Noteworthy space telescopes for the study of galaxies include the Hubble Space Telescope (HST),

Spitzer Space Telescope (SST), the Galaxy Evolution Explorer (GALEX) and many more (Scoville et al., 2007; Werner et al., 2004; Martin et al., 2005). Ground-based telescopes for the study of galaxies include the Hobby-Eberly Telescope (HET) in Texas, USA, and the Southern African Large Telescope (SALT) in Sutherland, South Africa. For our research purposes, we study the spatially-resolved stellar kinematics and stellar populations of a set of galaxies with the SALT telescope.

Throughout sections 1.1.1 to section 1.1.4, we discuss galaxy morphology, the modern theories of “the cosmic web”, as well as the hierarchical growth of galaxies and their scaling relations. We also provide a brief overview of HI galaxies and active galactic nuclei (AGN) in section 1.1.5. All of the aforementioned information provides a general understanding of galaxy evolution, which is necessary before delving into the specialised topics such as the stellar kinematics and stellar populations of galaxies.

In section 1.2, we discuss the stellar kinematics of galaxies, such as the fundamental kinematic properties of galaxies and how this information can be used to investigate the dark matter content within galaxies.

In section 1.3, we discuss the stellar populations within galaxies and how these populations could have evolved over time. Here we briefly discuss stellar evolution, stellar spectra and the initial mass function (IMF) of stellar populations.

In section 1.4, we discuss galaxy spectra, which will be the type of data we analyse in this thesis. Here we discuss how to measure stellar kinematics from galaxy spectra as well as how to model stellar populations for galaxy spectra using stellar populations synthesis (SPS). We also give a brief summary of stellar libraries, which is necessary when performing SPS and fitting galaxy spectra.

In section 2.3, we discuss how the SALT Robert Stobie Spectrograph works and how we obtained our data for our research using this instrument.

Finally, in 1.5, we discuss and motivate the purpose of our original research.

1.1.1 Galaxy Classification by Morphology

There exists a wide array of galaxies of various colours, sizes and morphologies (shapes) throughout the Universe (Mo et al., 2010). It has been found that several of a galaxy’s properties, such as its colour, mass, age, content and activity are related to its morphology. Therefore, to study galaxies effectively, we need to understand what morphology a galaxy can have and how this may evolve over cosmological time.

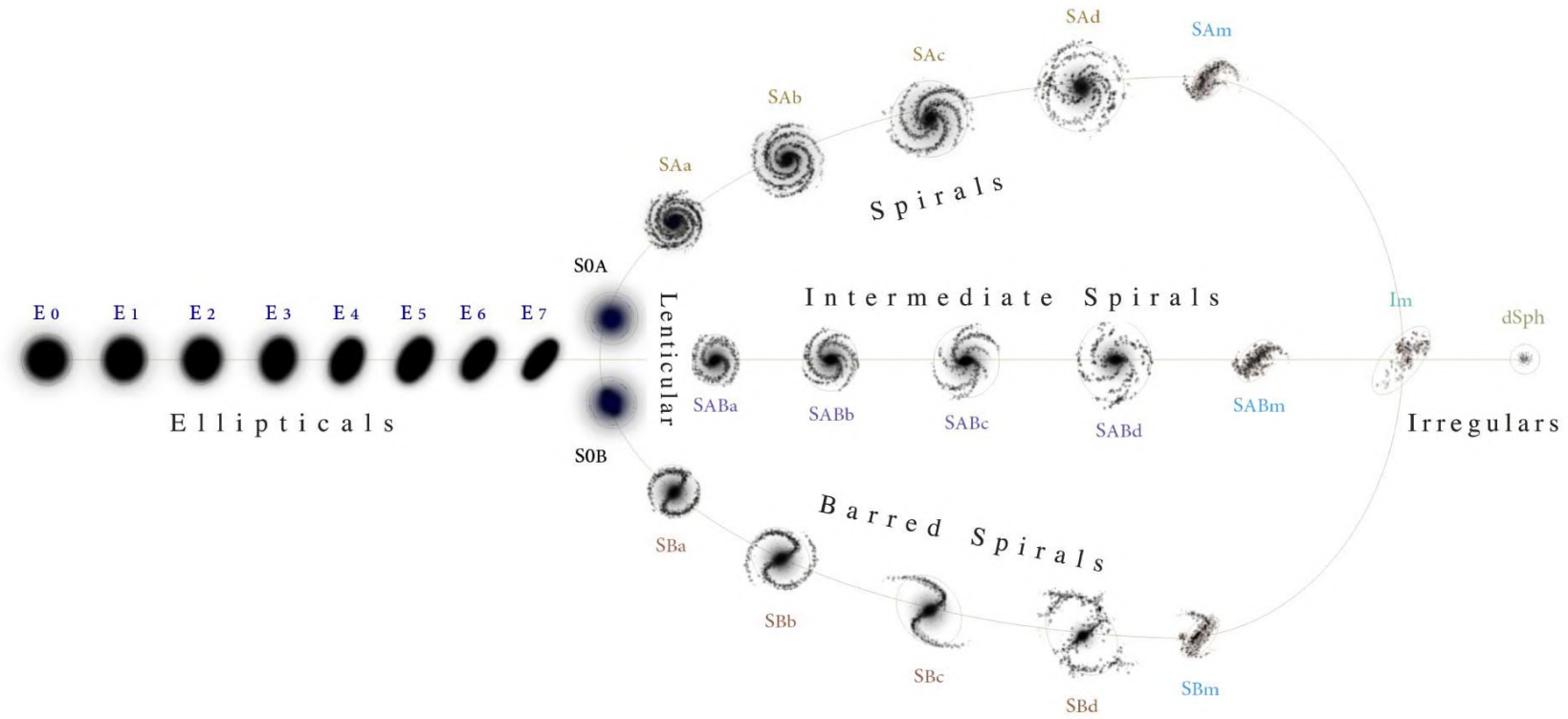


Figure 1.1: Hubble-De Vaucouleurs Diagram, also known as the “Hubble Tuning Fork”, which categorises galaxies by their morphology. From left to right: early-type galaxies (ellipticals and lenticulars), late-type galaxies (spirals) and irregulars. Image credit: https://commons.wikimedia.org/wiki/File:Hubble_-_de_Vaucouleurs_Galaxy_Morphology_Diagram.png

As shown in Figure 1.1, the elliptical galaxies are labelled E0 to E7, which follows Hubble’s classification scheme (Hubble, 1982). The digit following the letter ‘E’ is based on the ellipticity of the galaxy, where more elliptical galaxies have a higher number. This number can be calculated with equation 1.1.

$$E = 10 \times \left(1 - \frac{b}{a}\right) \quad (1.1)$$

where $\frac{b}{a}$ is the ratio of the galaxy’s minor axis (b) to its major axis (a).

The late-type galaxies are divided into three categories and follow van den Bergh’s classification scheme (Van den Bergh, S., 1976). These categories are: Spirals, (Prefix: SA): SAa, SAb, SAc, SAd and SAM, named in descending order of the tightness of their spiral arms; Intermediate Spirals (Prefix: SAB), SABa, SABb, SABc, SABd and SABm, similarly named to classic spirals; and Barred Spirals (Prefix: SB), SBa, SBb, SBc, SBd and SBm, similarly named.

It can be asked: “How common is each morphology type of galaxy? Furthermore, where can these galaxies be found? Are they isolated and far in between, or do they form part of a larger system?” To answer these questions, we need to consider the large-scale structure of the Universe and where galaxies can be found on the so-called “cosmic web”.

1.1.2 The Cosmic Web, the Large-Scale Structure of the Universe and the Distribution of Galaxies

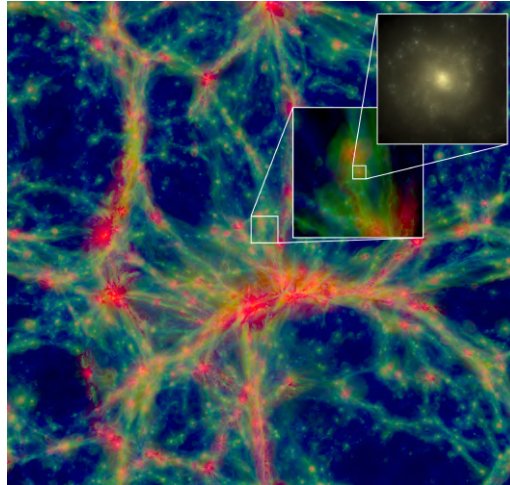


Figure 1.2: A piece of the Universe as simulated by the EAGLE project (Schaye et al., 2015). The image shows the “cosmic web”, the web-like megastructure of dark matter within the Universe (Ferreras, 2019).

As shown in Figure 1.2, dark matter permeates the Universe in a web-like (filament-like) megastructure. Dark matter emits no electromagnetic radiation and can therefore not be seen or detected directly by our telescopes. However, dark matter does act out a gravitational force similar to ordinary (baryonic) matter and can therefore be observed indirectly and simulated computationally (Ferrerias, 2019). Dark matter far outweighs the amount of ordinary matter throughout the Universe with a ratio of $\sim 6 : 1$ (Ferrerias, 2019). Roughly 24 % of the matter and energy content of the Universe is in the form of dark matter, whereas only ~ 6 % is in the form of baryonic matter (Ferrerias, 2019). The remaining 72 % is in the form of dark energy, which is still poorly understood.

Galaxies in the Universe can be found in a variety of environments, namely galaxy groups, galaxy clusters, fields and voids (Ferrerias, 2019). Galaxy groups and clusters are the largest gravitationally bound structures within the Universe and can be found at the intersections of dark matter filaments on the cosmic web. The vast spaces between each filament are called fields and contain only a handful of galaxies; the areas containing no known galaxies are called voids (Ferrerias, 2019). Clusters are extremely dense gravitationally bound environments, typically spanning ~ 2 megaparsec across in diameter (Schneider, 2006). Clusters typically contain 50 galaxies per megaparsec. The most massive galaxies within clusters may have a luminosity of $\gtrsim 2 \times 10^{10} L_{\odot}$ and a mass of $10^{13} M_{\odot} \lesssim M \lesssim 10^{15} M_{\odot}$ (Sparke and Gallagher III, 2007). However, clusters may also contain a large number of fainter and less massive dwarf- and satellite galaxies. Groups are smaller and poorer systems, typically spanning ~ 0.5 megaparsec across in diameter (Schneider, 2006). In comparison, the most massive galaxies within groups may have a mass of $10^{11} M_{\odot} \lesssim M \lesssim 10^{13} M_{\odot}$ (Sparke and Gallagher III, 2007).

Early-type galaxies, the main subject of this thesis, are most commonly found in the densest regions of groups and clusters (Ferrerias, 2019). In contrast, late-type galaxies are most commonly found on the outskirts of groups and clusters, as well as in fields (Ferrerias, 2019). There exists a strong connection between the evolution of galaxies, their dark matter content and their larger environment. This theory is known as the hierarchical growth of galaxies.

1.1.3 Hierarchical Growth and Evolution of Galaxies

Originally, it was thought that elliptical galaxies evolve into spiral galaxies and therefore these types of galaxies were referred to “early-type” and “late-type” galaxies (Ellis et al., 2000). Astronomers still use this naming convention today. It was believed that galaxies form from the gravitational collapse of monolithic cold-gas clouds (Ellis et al., 2000). Later supernovae feedback within the galaxy would then remove the excess cold-gas and form an elliptical galaxy (Ellis et al., 2000). The gas and dust in this elliptical galaxy would

then dissipate over time due to dynamical instability and form a spiral galaxy (Ellis et al., 2000). However, this picture is inaccurate, as it does not take into account the role of dark matter in galaxy evolution, which was unknown at the time (Ellis et al., 2000). In contemporary times, we have a much clearer picture of the role that dark matter plays in galaxy evolution. We now know that dark matter makes up the majority, $\sim 85\%$, of a galaxy's mass in the form of a halo and is fundamental to a galaxy's growth (Ferreras, 2019).

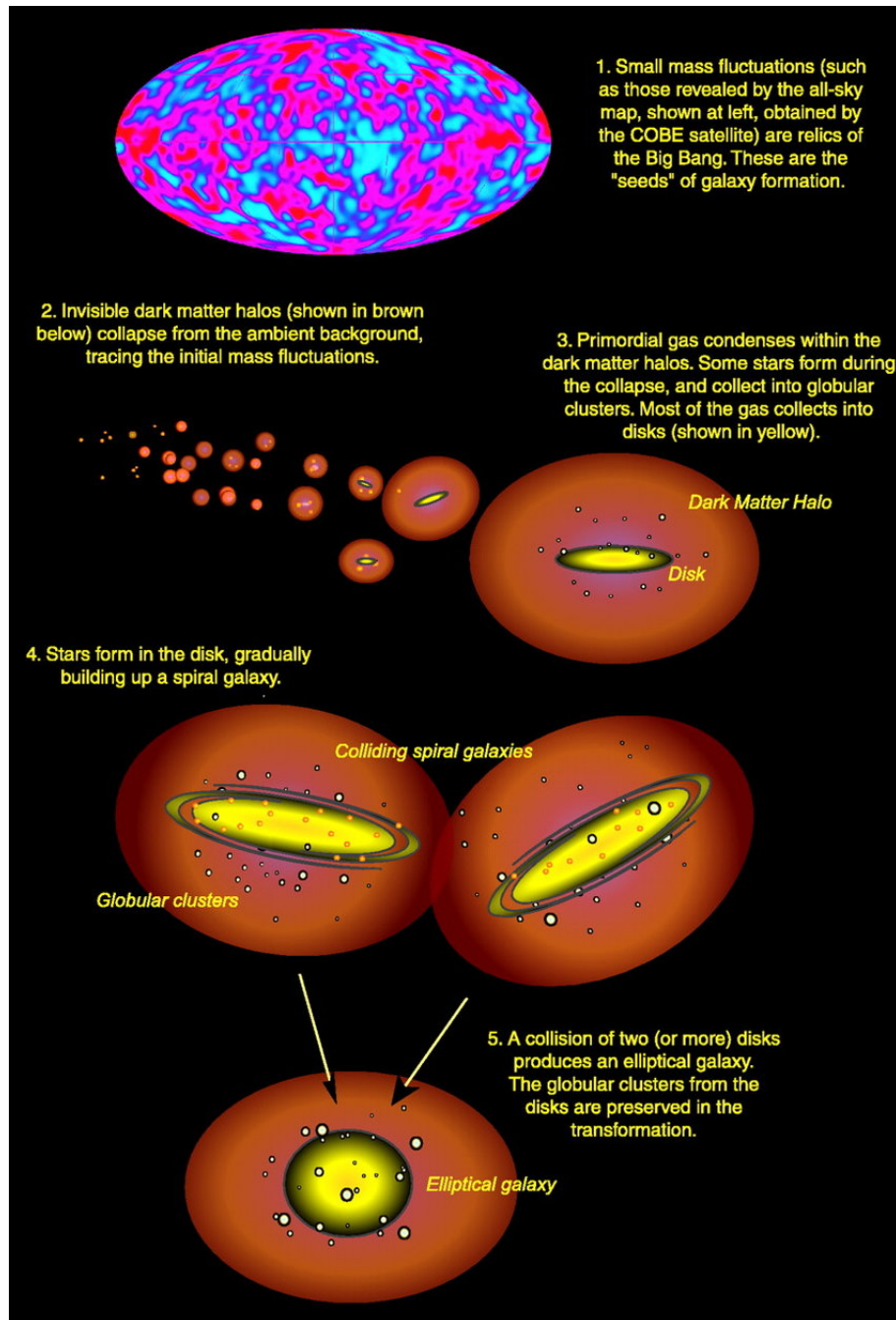


Figure 1.3: An illustration of hierarchical growth (Abraham and van den Bergh, 2001).

As illustrated in Figure 1.3, it is primarily the strong gravitational attraction of dark matter haloes, due to their mass, that causes galaxies to merge and to hierarchically evolve into more massive galaxies. Astronomers scarcely know of any galaxies without a dark matter halo, save a handful of very exceptional cases such as NGC 1052-DF2 and NGC 1052-DF4 (Van Dokkum et al., 2018; Van Dokkum et al., 2019). According to this theory, the first galaxies to form are spiral (late-type) galaxies, thought to originate from the condensing primordial gas within dark matter haloes. These galaxies later collide to form heavier elliptical and lenticular (early-type) galaxies.

For each type of galaxy (early-type or late-type), we can observe certain trends or “scaling relations”. We can statistically describe large quantities of galaxies together with these scaling relations.

1.1.4 Scaling Relations for Galaxies

Scaling relations are empirically derived trends that relate several of a galaxy’s fundamental properties with one another, such as its mass, luminosity and kinematic properties. There are unique scaling relations for both early-type galaxies and late-type galaxies, respectively. The most important scaling relations are given below.

The Faber-Jackson Relation: The total luminosity L of an early-type galaxy is related to its velocity dispersion σ as (Faber and Jackson, 1976; Ferreras, 2019):

$$L \propto \sigma^\alpha \quad (1.2)$$

where $\alpha \sim 4$. This scaling relation can intuitively be understood by considering the fact that the majority of an early-type galaxy’s kinetic energy is a result of the velocity dispersion of its stars.

The Kormendy Relation: An early-type galaxy’s surface brightness Σ is related to its size R as (Hamabe and Kormendy, 1987; Ferreras, 2019):

$$\Sigma \propto R^\gamma \quad (1.3)$$

where $\gamma \sim -3$. More plainly stated, the larger the early-type galaxy, the fainter it appears in comparison with other early-type galaxies.

The Fundamental Plane: The two previously named scaling relations can be combined to form the Fundamental Plane. This theorem states that an early-type galaxy’s size R is

related to its velocity dispersion σ and average surface brightness Σ as:

$$R \propto \sigma^{1.2} \Sigma^{-0.8} \quad (1.4)$$

The Fundamental Plane can be used to gain insight into the formation and evolution of early-type galaxies.

The Tully-Fisher Relation: Similar to the Faber-Jackson relation for early-type galaxies, late-type galaxies have a similar relation called the Tully-Fisher relation. For a late-type galaxy, its total luminosity L is related to its apparent surface brightness Σ and rotational velocity V as (Tully and Fisher, 1977; Ferreras, 2019):

$$L \propto \Upsilon^{-2} \Sigma^{-1} V^4 \quad (1.5)$$

where $\Upsilon = \frac{M}{L}$ is the observationally determined mass-to-light ratio of the galaxy.

In our research, we will be studying the stellar kinematics of several early-type galaxies. In particular we will be using the Faber-Jackson Relation.

Before delving into the primary topics of our research, the stellar kinematics and stellar populations of galaxies, it is worth noting some other properties that could be encountered. Some of these properties include the HI content contained within galaxies and active galactic nuclei (AGN).

1.1.1.5 The HI Content in Galaxies and Active Galactic Nuclei

The HI Content within Galaxies: Hydrogen is the most abundant element found within the Universe, making up about 75 % of all baryonic matter (Mukhanov, 2005). In Astronomy, we make a distinction between neutral atomic hydrogen, referred to as HI, and ionised hydrogen, referred to as HII. HI regions within galaxies can be observed by the characteristic 21 cm resonant emission from neutral hydrogen (Ferreras, 2019).

HI is more abundant in late-type galaxies than early-type galaxies, since HI is more prevalent in the early evolutionary stages of galaxies (Lewis and Davies, 1973). By studying the HI content of galaxies, we can better understand their formation, their internal processes and how they might relate to their environment (Acosta-Pulido et al., 2015). These processes include star-formation (SF), both in and beyond the galactic disc, which ultimately shape the structure of the galaxy (Acosta-Pulido et al., 2015). The HI mapping of nearby late-type galaxies is one of the main research objectives of the upcoming Square Kilo-

meter Array (SKA) project, as well as the ongoing MHONGOOSE Large Survey Project by MeerKAT (Acosta-Pulido et al., 2015; Sorgho et al., 2019). In this thesis, we will be studying a specific MHONGOOSE galaxy, as later discussed in section 2.2.

Active galactic nuclei (AGN): It is well-established that supermassive black holes occupy the centres of massive galaxies (Kormendy and Richstone, 1995). The evolution of the black hole and the galaxy itself is strongly coupled (Kormendy and Richstone, 1995). Some galaxies with strongly accreting black holes emit significant amounts of radiation from their cores (Kormendy and Richstone, 1995). These galaxies are known as active galactic nuclei (AGN).

Some AGNs are accompanied by bipolar relativistic jets (Sparke and Gallagher III, 2007). These jets typically radiate the strongest in X-ray and gamma wavelengths, but may span over the entire electromagnetic spectrum (Sparke and Gallagher III, 2007). AGN-feedback, the systematic heating of gas throughout the interstellar medium (ISM) of a galaxy, is a complex subject, still poorly understood by astronomers (Böttcher et al., 2012). This AGN-feedback may influence the star-formation activity within a galaxy by heating and expelling gas, which would otherwise have formed stars (Böttcher et al., 2012). What particles these jets consist of is not well understood and is an ongoing debate (Böttcher et al., 2012). These jets have various components that can be observed in optical and radio wavelengths (Böttcher et al., 2012). Based on the optical and radio properties of AGN, these galaxies can be divided into several categories. There are several categories of AGN, such as low-ionization nuclear emission-line region (LINER) galaxies, Seyfert galaxies (type I and II), blazars, quasars and others (Böttcher et al., 2012).

AGN activity is particularly common in environments such as galaxy clusters, but also prevalent in galaxy groups (Lilly et al., 2009). Some of the Complete Local-Volume Groups Sample (CLOGS) brightest group early-type galaxies (BGEs) are known to have AGN activity, such as 92 % of the high-richness sub-sample (Kolokythas et al., 2018). This sample is discussed further in 2.1. Their AGN activity may influence their star-formation properties. Therefore, when we discuss the stellar populations of the CLOGS BGEs in Chapter 4 of this thesis, we will take into account the possibility of AGN activity.

1.2 Stellar Kinematics of Galaxies

The primary topics of this thesis are the spatially-resolved stellar kinematics and stellar populations of a select sample of galaxies (listed in Chapter 2). This section deals with the most important concepts concerning the stellar kinematics of galaxies - the first theme of this thesis. These concepts are stellar rotational velocity and stellar velocity dispersion.

1.2.1 Stellar Rotational Velocity and Stellar Velocity Dispersion

Stellar rotational velocity: A galaxy's stellar rotational velocity is the sum total rotational (orbital) velocity of its stars (Sparke and Gallagher III, 2007). The orbit of a star with centripetal acceleration $V^2(r)/r$, with rotational velocity $V(r)$ at radius r from the galactic centre is determined by the inward gravitational force F_r of the galaxy (Sparke and Gallagher III, 2007).

$$\frac{V^2(r)}{r} = -F_r \quad (1.6)$$

The inward gravitational force can be determined with the gradient of the gravitational potential Φ of the galaxy (Sparke and Gallagher III, 2007).

$$F_r(r) = -\nabla\Phi_r(r) \quad (1.7)$$

A simple yet effective way to determine the gravitational potential of a galaxy is to solve Poisson's equation for gravity (Sparke and Gallagher III, 2007):

$$\nabla^2\Phi(\vec{r}) = 4\pi G\rho(\vec{r}) \quad (1.8)$$

where $\rho(\vec{r})$ is the density profile of the galaxy. In reality, each galaxy would have a unique density profile. Due to the vastly different structures of early-type and late-type galaxies, they would naturally have different density profiles.

For an early-type galaxy, its structure can be approximated as spherically symmetric and its density profile can be described with the Plummer sphere (Plummer, 1911):

$$\rho_P(r) = \frac{3M}{4\pi a^3} \left(1 + \frac{r^2}{a^2}\right)^{-\frac{5}{2}} \quad (1.9)$$

where a is the scaling parameter that sets the size of the galaxy. More contemporary and arguably more accurate models include Hernquist's and Jaffe's models for early-type galaxies.

Hernquist defines the density profile of an early-type galaxy as (Hernquist, 1990):

$$p_H(r) = \frac{M}{2\pi} \frac{a}{r(r+a)^3} \quad (1.10)$$

where a is the scaling parameter, similar as before. The model of Hernquist (1990) was derived using a numerical simulation of the merging process of two equal mass dark matter haloes. For this reason, this model is appealing to use for astronomers as it takes into account the theory of hierarchical growth of galaxies.

Jaffe (1983) has a similar model with a slightly different density profile for an early-type galaxy (Ferreras, 2019):

$$p_J(r) = \frac{M}{4\pi} \frac{a}{r^2(r+a)^2} \quad (1.11)$$

The model of Plummer (1911) was later modified to approximate the density profile of late-type galaxies. Kuzmin theorem's states that the initial surface density Σ of a late-type galaxy can be approximated as (Ferreras, 2019):

$$\Sigma(r) = \frac{M}{2\pi a^2} \left(1 + \frac{r^2}{a^2}\right)^{-\frac{5}{2}} \quad (1.12)$$

where a is the scaling parameter to set the size of the galaxy. Using these different density profiles (such as equations 1.9, 1.10, 1.11 and 1.12), Poisson's equation (equation 1.8) can be solved to obtain the gravitational potential Φ of the chosen model. With the gravitational potential of the galaxy now known, we can calculate the inward gravitational force of the galaxy with equation 1.7 to ultimately obtain the rotational velocities $V(r)$ of the stars in the galaxy with equation 1.6. In this thesis, we will obtain results computationally by fitting galaxy spectra with full-spectrum fitting software, described in Chapter 2. Although our results are found by fitting galaxy spectra, it is important to understand how the stellar rotational velocity physically relates to the gravitational potential of the galaxy - as previously described.

Stellar velocity dispersion: The stellar velocity dispersion σ of a galaxy is simply the root-mean-square deviation from the average velocity of the stars in the galaxy (Ferreras, 2019). This is a many-body problem since galaxies have a multitude of stars distributed throughout phase space at various different positions and velocities (Ferreras, 2019). Therefore, we need to define a distribution function $f(\vec{r}, \vec{v}, t)$ to describe the number of stars for each differential volume throughout phase space $d\tau = d^3r d^3v$ (Ferreras, 2019).

This allows us to write the velocities of the stars in the galaxy as (Ferreras, 2019):

$$v(\vec{r}, t) \equiv \iiint f(\vec{r}, \vec{v}, t) d^3v \quad (1.13)$$

and furthermore to write the average velocity of the stars in the galaxy as (Ferreras, 2019):

$$\langle \vec{v}(\vec{r}, t) \rangle \equiv \frac{1}{v(\vec{r}, t)} \iiint f(\vec{r}, \vec{v}, t) d^3v \quad (1.14)$$

From equations 1.13 and 1.14, we can easily calculate the velocity dispersion of the stars in the galaxy as (Ferreras, 2019):

$$\sigma \equiv \sqrt{\langle v^2(\vec{r}, t) \rangle - \langle \vec{v}(\vec{r}, t) \rangle^2} \quad (1.15)$$

The stellar velocity dispersion can also be calculated via the variance of the velocities as (Ferreras, 2019):

$$\sigma^2 \equiv \langle v^2(\vec{r}, t) \rangle - \langle \vec{v}(\vec{r}, t) \rangle^2 \quad (1.16)$$

The simplest distribution function for an early-type galaxy is that of an isothermal sphere, known as (Ferreras, 2019):

$$f(\epsilon) = \begin{cases} Ae^{\epsilon/\sigma^2} & \epsilon \geq 0 \\ 0 & \epsilon \leq 0 \end{cases} \quad (1.17)$$

$$(1.18)$$

where ϵ is the relative energy, σ is the velocity dispersion and A is the normalisation constant. This distribution function is analogous to the Maxwell-Boltzmann distribution in thermodynamics.

Similarly, the simplest distribution function for a late-type galaxy is the Mestel disc, known as (Ferreras, 2019):

$$f(\epsilon) = \begin{cases} A(\frac{J_z}{R_0 v_0})^q e^{\frac{\epsilon}{\sigma^2}} & \epsilon \geq 0 \\ 0 & \epsilon \leq 0 \end{cases} \quad (1.19)$$

$$(1.20)$$

where J_z is the vertical component of the angular momentum and q is the power-law constant. Similar to equation 1.17, A is the normalisation constant, ϵ is the relative energy and σ is the velocity dispersion.

An angular momentum term is included in this function to account for the rotation of the stars within the galactic disc. Stars within late-type galaxies move more uniformly (as

they move through certain channels or arms), whereas the motion of stars in early-type galaxies are more random and in all directions (isotropic). This is one of the fundamental differences between early-type and late-type galaxies.

Pressure supported galaxies and rotationally supported galaxies: Early-type galaxies and late-type galaxies have significantly different rotational velocities and stellar velocity dispersions (Davies et al., 1983). The structure of early-type galaxies is mostly supported by the random thermal motion of stars in their system. In contrast, the structure of late-type galaxies is mostly supported by its rotation (Davies et al., 1983). This concept is illustrated in Figure 1.4.

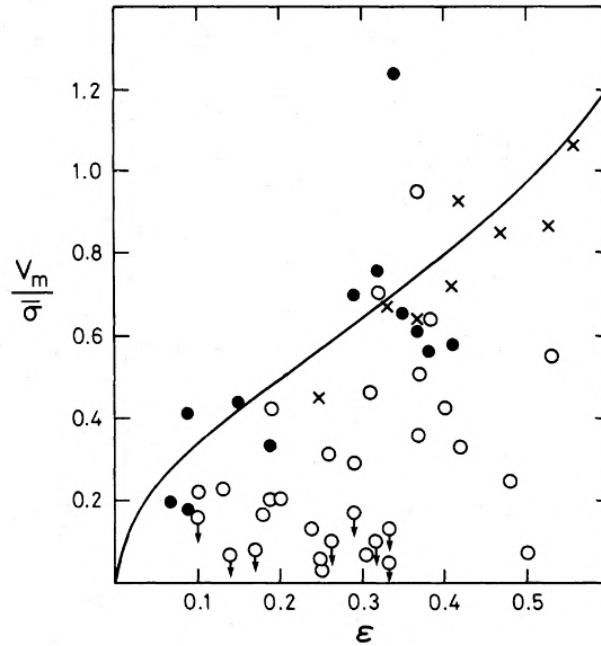


Figure 1.4: Illustration of the difference between rotationally supported and pressure supported galaxies (Davies et al., 1983). Early-type galaxies with a magnitude of $M_B^{UH} > -20.5$ are shown by the filled circles and early-type galaxies with a magnitude of $M_B^{UH} < -20.5$ are shown by the empty circles. The crosses indicate late-type galaxies. The solid curved line on the figure represents the expected $\frac{V_m}{\sigma}$ (maximum stellar rotational velocity over the average stellar velocity dispersion) relation for oblate galaxies with an isotropic velocity dispersion (Binney, J., and Silk, J., 1978).

^{1 2} Galaxies below the solid line on Figure 1.4 (typically early-type galaxies) have a much lower $\frac{V_m}{\sigma}$ (lower maximum rotational velocity and higher average velocity dispersion) and are therefore pressure supported. Galaxies on and above the line (typically late-type

¹ M_B^{UH} : Absolute magnitude of the galaxy measured in the B^{UH} waveband. ‘B’ refers to blue, ‘UH’ refers to “ultra-high frequency”.

² Oblate galaxy: An elliptical galaxy which is wider at its horizontal axis than its vertical axis.

galaxies) have a higher $\frac{V_m}{\sigma}$ (higher maximum rotational velocity and lower average velocity dispersion) and are therefore rotationally supported. In this thesis, we will generate a figure similar to Figure 1.4 to characterise our sample of galaxies (listed in Chapter 2) according to their rotation. Since the stellar kinematics of galaxies are tied to its gravitational potential, we can relate the stellar kinematics of galaxies to their material content. This would include the galaxy's gas and dust, stellar material and dark matter content.

1.2.2 Investigating the Dark Matter Content within Galaxies with Stellar Kinematic Measurements

Galaxies consist of a dusty and gaseous interstellar medium (ISM), in which stars may form, a unique distribution of stars and a dark matter halo (Ferreras, 2019). The process of star-formation and their evolution is further described in section 1.3.1. A galaxy's rotational kinetic energy is supplied by its ISM (gas and dust), its stellar population and its dark matter halo in order of increasing contribution (increasing mass) (Ferreras, 2019). Figure 1.5 shows the rotational velocity curve for NGC 6503 (as an example) - a nearby dwarf spiral galaxy.

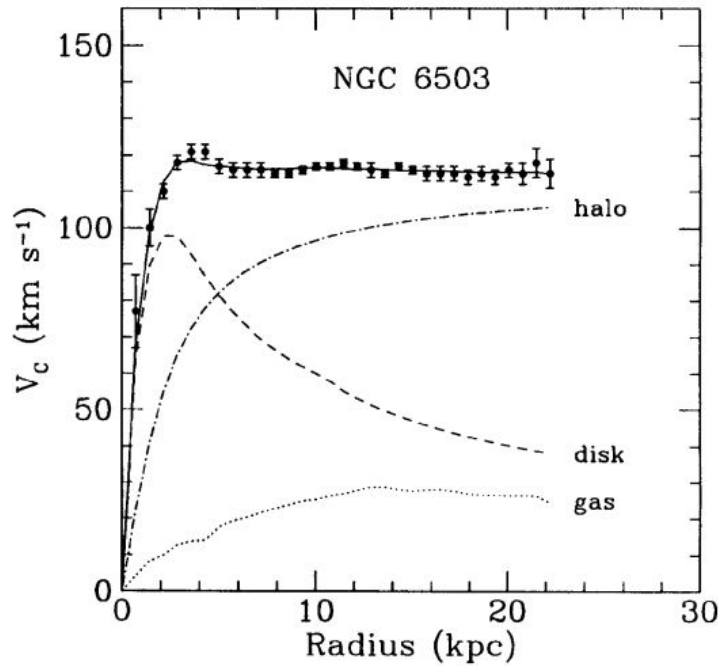


Figure 1.5: Rotational velocity curve of NGC 6503 in terms of its rotational velocity components V_c and radius from galactic centre (Doroshkevich et al., 2012). Image credit: <https://ned.ipac.caltech.edu/level5/Sept17/Freese/Freese2.html>

As shown in Figure 1.5, the rotational velocity of the stellar population peaks at the galaxy's central bulge and decreases outwards with radius. In contrast, the rotational

velocity of dark matter halo increases from the galactic centre to a point and then remains roughly constant with radius.

In fact, this is how earlier astronomers such as Babcock (1939) and Freeman (1970) first discovered dark matter within galaxies. They observed the rotation curves of galaxies and concluded that the mass of their ISM and their stellar populations are insufficient to support their structures. An amount of missing invisible matter is required to explain the galaxy's rotation and structure. This missing matter is what astronomers call dark matter, as originally discovered and coined by (Zwicky, 1937; Perlov and Vilenkin, 2017). It is believed that dark matter must consist of some type of exotic and unknown type of particle(s) that do not interact with electromagnetic radiation (Perlov and Vilenkin, 2017). Although astronomers cannot observe dark matter directly, it can be observed indirectly by studying gravitational phenomena, such as the rotation of stars within galaxies.

When we interpret our stellar kinematic results in Chapter 4, we will allude to the presence of dark matter within our sample of galaxies. To constrain the dark matter content within galaxies is one of the latest research objectives in extragalactic astronomy.

1.3 Stellar Populations within Galaxies

The second theme of this thesis, is the stellar populations of our sample of galaxies, listed in Chapter 2. In order to understand the evolution of galaxies, it is necessary to understand how their stellar populations may evolve over time. In this section, the relevant background information concerning stellar evolution is given.

This section summarises stellar evolution, from the formation (birth) of a star, its evolution during its lifetime and its final evolutionary stages (death). Furthermore, this section will describe in detail the features of stellar spectra - which is an essential component of galactic spectra, which we wish to study in this thesis. This section will also describe the IMF of stars, which is an essential ingredient when modeling stellar populations.

1.3.1 An Overview of Stellar Evolution

Birth of a star: We know that the Universe consists primarily out of dark matter ($\sim 25\%$) and dark energy ($\sim 70\%$) (Mukhanov, 2005). The remaining amount consists of baryonic matter ($\lesssim 5\%$), which is mainly composed out of hydrogen ($\sim 75\%$), helium ($\sim 25\%$) and small traces of heavier elements ($\lesssim 1\%$) (Mukhanov, 2005). Baryonic matter is scattered throughout the ISM in the form of dust and gas (Carroll and Ostlie, 2017). Molecular gas may form clouds in cold and dense regions of the ISM (Carroll and Ostlie,

2017). In these regions, the molecular gas clouds may collapse under its own self-gravity and trigger the thermonuclear fusion of hydrogen, the birth of a proto-star, a pre-main-sequence star (Carroll and Ostlie, 2017). Figure 1.6, the “Hayashi Track”, provides a summary of the evolutionary tracks of pre-main-sequence stars based on their mass and temperature.

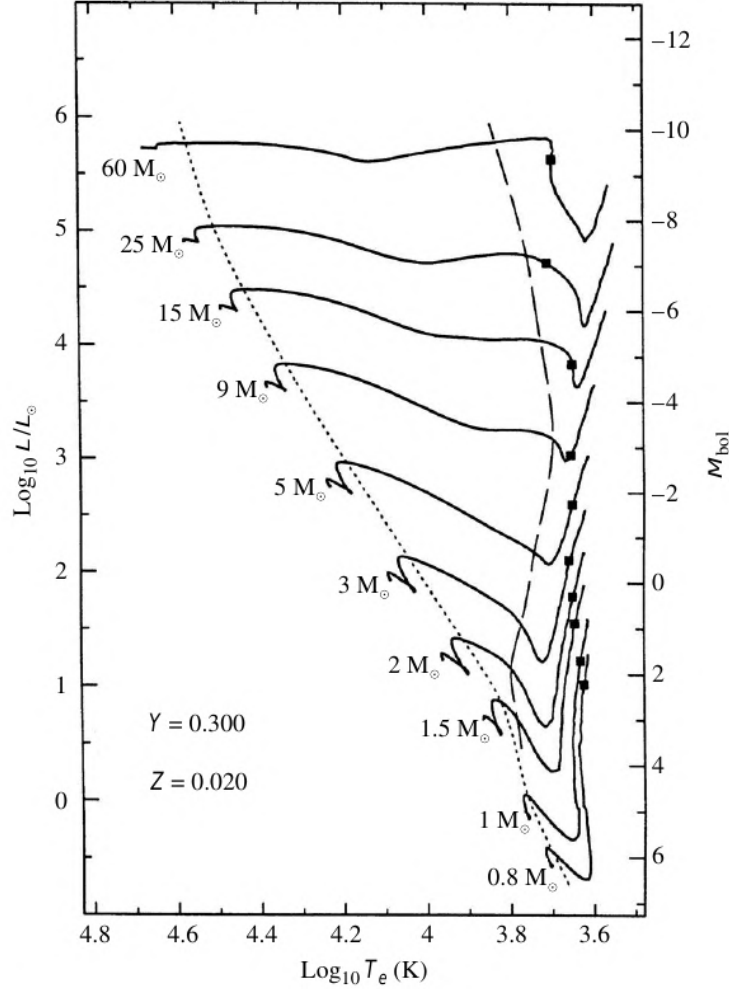


Figure 1.6: Hayashi evolutionary tracks for pre-main-sequence stars of various masses with metallicities $X = 0.68$ (fraction of hydrogen), $Y = 0.3$ (fraction of helium) and $Z = 0.02$ (fraction of metals, e.g. heavier elements) (Carroll and Ostlie, 2017).

Life of a star: After the protostars have reached hydrostatic equilibrium, they are called main-sequence stars. Depending on their initial mass and chemical supply, they may further evolve into subgiants, giants or even supergiants (Carroll and Ostlie, 2017). The Hertzsprung-Russell diagram of Hertzsprung (1909) and Russell (1914), shown in Figure 1.7, summarises the possible evolution tracks of main sequence stars. Figure 1.7 shows the evolutionary tracks of stars based on their (B-V) colour and visual luminosity.

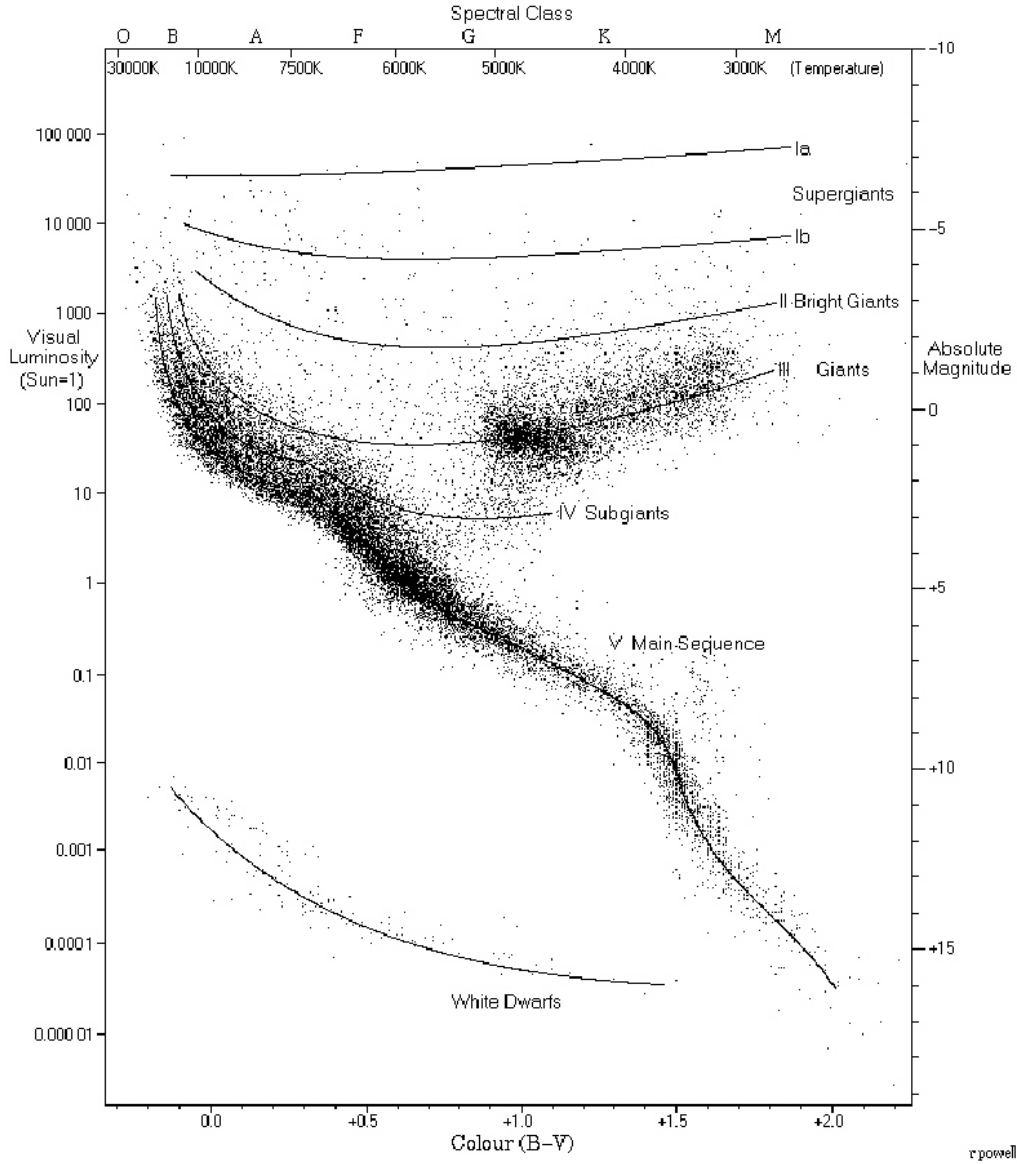


Figure 1.7: Hertzsprung-Russel (HR) diagram based on the earlier work of Hertzsprung (1909) (Russell, 1914). The diagram depicts the various types of stars according to their Morgan-Keenan spectral class (O, B, A, F, G, K, M in descending order of temperature) and luminosity class (from I - V in descending order of brightness). Image credit: https://www.researchgate.net/figure/The-Hertzsprung-Russel-HR-diagram-for-a-representative-sample-of-stars-22000-stars_fig2_273704372

The spectral classes categorise stars according to their temperature and spectral characteristics (Mo et al., 2010). These spectral classes are further subdivided with a digit, with 0 indicating the hottest type of star and 9 indicating the coolest (Mo et al., 2010), i.e: B0, B1, ... B9. The spectral classes are defined in Table 1.1 below:

Table 1.1: Spectral classes for stars, with their corresponding colours, temperature ranges and spectral characteristics, according to Karttunen et al. (2007) and Morgan and Keenan (1973).

Spectral class	Temperature range	Most important spectral characteristics
O (Blue)	28 000 - 50 000 K	Weak HI. Visible HeI. Strong HeII, CIII, NIII and OIII.
B (Blue-White)	10 000 - 28 000 K	Visible OII, SiII, MgII, K (at B3) and CaII (at B3). Strong HeI.
A (White)	7 500 - 10 000 K	Visible neutral metals. Strong H, K, CaII and HI (at A0).
F (Yellow-White)	6 000 - 75 000 K	Many metal lines e.g. FeI, FeII. Strong H, K and Ca II.
G (Yellow)	5 000 - 6 000 K	Very strong H and K. Weaker HI.
K (Orange)	3 000 - 5 000 K	Dominated by metal lines. Insignificant HI. Strong H and K.
M (Orange-Red)	2 500 - 3 500 K	Many neutral metal lines. Very strong CaI.

The list of spectral characteristics listed in Table 1.1 is by no means complete, as there is a vast multitude of absorption and emission features for every single atomic and molecular combination. The luminosity classes indicated on the HR diagram (Figure 1.7) are defined in Table 1.2 below:

Table 1.2: Luminosity classes for stars with their corresponding luminosities as illustrated in Figure 1.7 (Morgan and Keenan, 1973).

Latin numeral	Name	Luminosity
I	Supergiants	$\sim 10^4 L_{\odot}$ to $\sim 10^6 L_{\odot}$
II	Bright Giants	$\sim 10^3 L_{\odot}$ to $\sim 10^4 L_{\odot}$
III	Giants	$\sim 10^2 L_{\odot}$ to $\sim 10^3 L_{\odot}$
IV	Subgiants	$\sim 10^1 L_{\odot}$ to $\sim 10^3 L_{\odot}$
V	Dwarfs (Main Sequence Stars)	$\sim 10^{-4} L_{\odot}$ to $\sim 10^3 L_{\odot}$

Death of a star: There are numerous possible endpoints for a star's life. The general evolutionary tracks of post-main-sequence massive stars are shown in Figure 1.8.

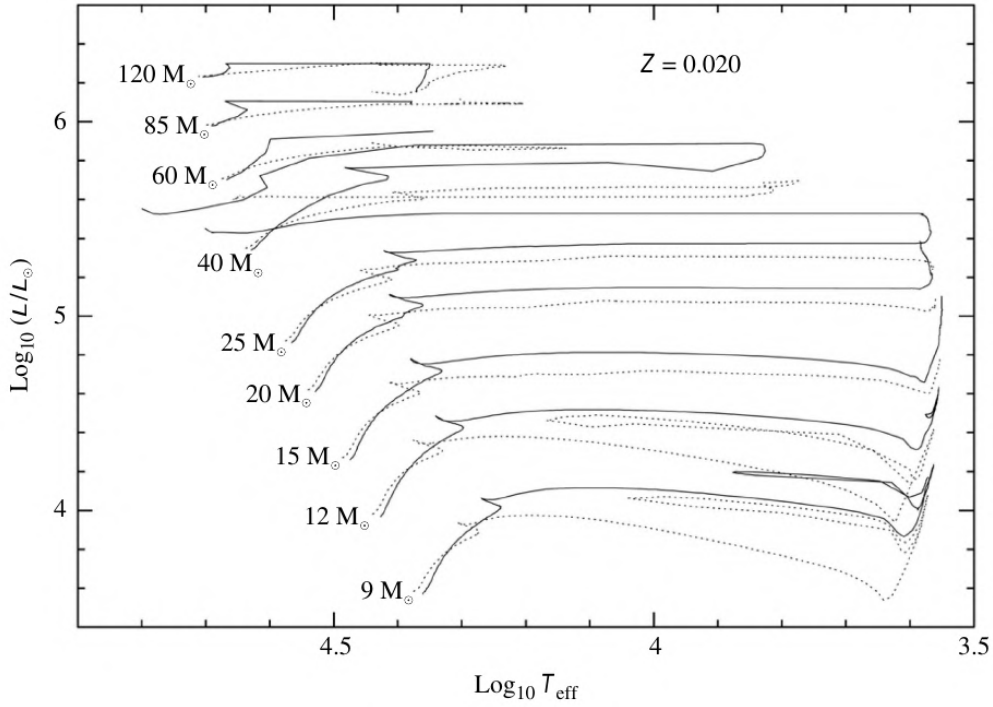


Figure 1.8: Evolutionary tracks of post-main-sequence massive stars with $Z = 0.02$, similar to Figure 1.6 (Meynet and Maeder, 2003; Carroll and Ostlie, 2017). The solid lines show the evolutionary tracks of stars with a rotational velocity of $\sim 300 \text{ km.s}^{-1}$, the dotted lines show the evolutionary tracks of non-rotating stars. The lives of these massive stars will all end in a supernova explosion as the star ultimately collapses under its self-gravity. These type of supernovae are classified as Type II or “core-collapse supernovae”. This type of supernovae show strong hydrogen emission lines on their spectra.

Figure 1.8 illustrated how massive stars may result in core-collapse supernovae, however supernovae may be caused by other means. For instance, a binary system of a white dwarf and a massive star may merge and cause a supernova explosion. These are known as Type I supernovae, which in contrast to Type II supernovae, do not show strong hydrogen emission lines on their spectra.

In contrast to massive stars, white dwarfs do not core-collapse in a supernova explosion, but rather degenerate into either a neutron star or a black hole singularity. After the white dwarf has quenched its nuclear supply to fuel its core, its inward self-gravity will overcome its outward radiation pressure and collapse in on itself (Tayler, 1994). The final stage of the white dwarf’s evolution depends on its initial mass before collapsing. White dwarfs that exceed the Chandrasekhar limit of $\sim 1.4 M_{\odot}$ but not the Tolman-Oppenheimer-Volkoff (TOV) limit of $\sim 2.3 M_{\odot}$ before collapsing will become neutron stars (Tayler, 1994). Stars that exceed the TOV limit will collapse and become a black hole singularity (Tayler, 1994).

1.3.2 Stellar Spectra

Stellar spectra consist of a continuum with narrow spectral emission and absorption lines superimposed on it (Karttunen et al., 2007). The continuum thermal radiation and spectral emission lines originate from the star’s surface, whereas the spectral absorption lines are caused by the stellar atmosphere absorbing certain wavelengths of radiation (due to its chemical composition) (Karttunen et al., 2007). To understand stellar spectra, we first need to understand some basic quantum mechanics, such as blackbody radiation, spectral emission and absorption, Doppler shift, spectral line broadening as well as some basic astronomy concepts such as redshift.

Planck’s theory of blackbody radiation: A blackbody is an ideal object that perfectly absorbs and re-emits electromagnetic radiation (Planck, 1914). Blackbodies emit a continuum of radiation according to Planck’s law (Planck, 1914):

$$B_\nu(T_b) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT_b} - 1} \quad (1.21)$$

where T_b is the blackbody temperature, h is Planck’s constant, ν is the frequency of the radiation and k is Boltzmann’s constant. Stars approximately behave as blackbodies.

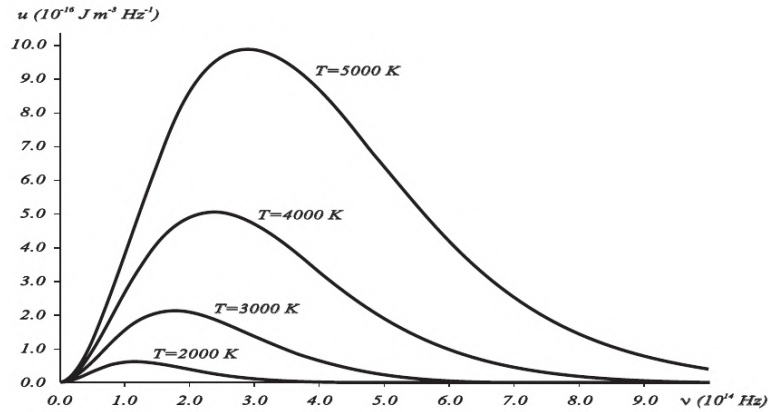


Figure 1.9: The spectral energy density in terms of frequency $u(\nu, T)$ of blackbodies at different temperatures, taken from Zettili (2003).

Spectral emission and absorption: It was Einstein et al. (1905) who stated that electromagnetic radiation consists of tiny packets of energy called “photons”. This laid the foundation for quantifying spectral emission and absorption lines. It was Planck (1914) who postulated that any quantum oscillator experiencing an energy change of ΔE will radiate (if energy was lost) or absorb (if energy was gained) a photon of frequency $\frac{\Delta E}{h}$, where h is Planck’s constant (Planck, 1914).

The emission of a photon by an atom or molecule may either be stimulated by another incoming photon, or occur spontaneously. The associated probabilities of these effects are given by the Einstein coefficients A_{21} for spontaneous emission, and B_{21} for stimulated emission (Tipler and Llewellyn, 2012). Conversely, the Einstein coefficient B_{12} gives the probability of an atom or molecule absorbing an incoming photon (Tipler and Llewellyn, 2012). These probabilities are known to relate with one another, as shown by equations 1.22 and 1.23 (Tipler and Llewellyn, 2012).

$$\frac{B_{12}}{B_{21}} = 1 \quad (1.22)$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad (1.23)$$

where h is Planck's constant, ν is the frequency of the photon, and c is the speed of light in a vacuum.

Neils Bohr, in 1913, with the knowledge of Einstein's theory of light and Planck's postulate, quantified the energy levels and spectrum of the hydrogen atom using Rutherford's atomic model (Zettili, 2003). The energy levels of the hydrogen atom are (Bohr, 1913):

$$E_n = -\frac{e^2}{8\pi\epsilon_0} \frac{1}{r_n} = -\frac{m_e}{2\hbar^2} \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \frac{1}{n^2} = -\frac{\mathcal{R}}{n^2} \quad (n = 1, 2, \dots, \infty) \quad (1.24)$$

where E_n are the energy levels and r_n are the radii of the electron orbiting the hydrogen nucleus at each level. ϵ_0 is the electric permittivity of free space, m_e is the mass of an electron, $\hbar$ is Planck's reduced constant and $\mathcal{R} = \frac{m_e}{2\hbar^2} \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 = 13.6 \text{ eV}$ is Rydberg's constant.

The negative sign in the energy levels of the hydrogen atom is due to the electron being in a bound state (Zettili, 2003). At higher energy levels, the electron's energy becomes increasingly closer to zero, i.e. closer to being freed from the atom (Zettili, 2003). Transitions to the 1st energy level are known as the Lyman series, transitions to the 2nd energy level are known as the Balmer series, and transitions to the 3rd energy level are known as the Paschen series.

Figure 1.10 shows the energy transitions of the hydrogen atom and illustrates the Lyman, Balmer and Paschen series. The hydrogen Lyman and Balmer series are of fundamental importance in stellar astronomy, as young main-sequence stars primarily burn hydrogen as a nuclear resource (Karttunen et al., 2007). Young main-sequence stars radiate a UV continuum with strong hydrogen (typically Balmer-series) absorption lines (Karttunen et al.,

2007).

As an example, the absorption lines of Vega and Aldebaran are shown in Figure 1.11. This shows how stars absorb and emit certain wavelengths based on their chemical composition.

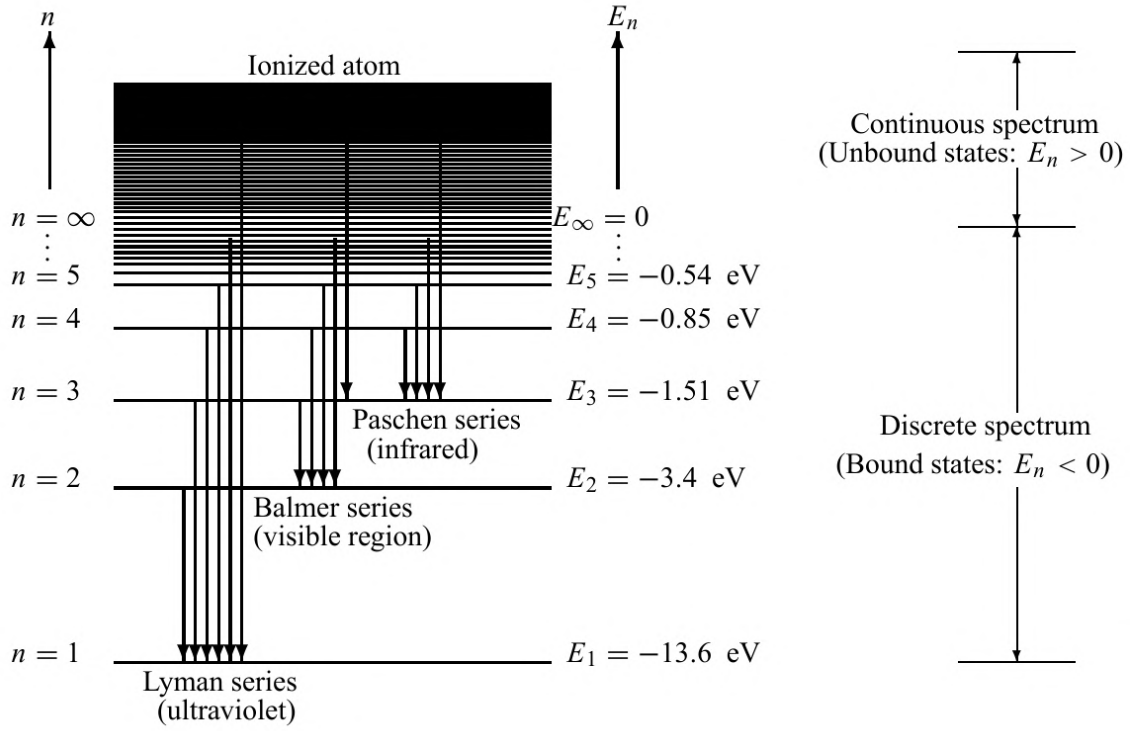


Figure 1.10: The energy transitions of the hydrogen atom (Zettili, 2003). The Lyman series radiates in ultraviolet light, the Balmer series radiates in visible light and the Paschen series radiates at infrared light.

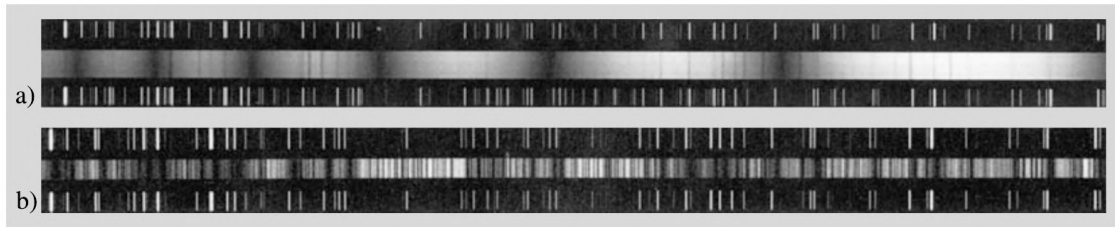


Figure 1.11: Absorption lines of (a) Vega, a A0 spectral type star and (b) Aldebaran, a K5 spectral type star (Karttunen et al., 2007). Vega emits a continuum in the UV range (375 – 390 nm) and strong Balmer absorption lines. Aldebaran, an older giant stars emits a fainter continuum with strong metal absorption lines.

Doppler shift: The Doppler effect is a very well-known physical effect (for both sound and light) described in nearly all high school and undergraduate Physics textbooks. When a source emitting electromagnetic radiation is moving with regards to the inertial frame of an observer, a shift in wavelength $\Delta\lambda$ will be observed proportional to the source's speed (Karttunen et al., 2007). The light from sources moving away from the observer is redshifted (an increase in wavelength is observed) and the light from sources moving towards the observer is blueshifted (a decrease in wavelength is observed). We can express this as:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c} \quad (v \ll c) \quad (1.25)$$

where λ_0 is the wavelength emitted by the source, v is the source's speed with regard to the observer and c is the speed of light in a vacuum. For a relativistically moving source, the formula is slightly adjusted as:

$$\frac{\Delta\lambda}{\lambda_0} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1 \quad (v \sim 0.7c \text{ to } v \sim c) \quad (1.26)$$

Redshift of galaxies: Light from galaxies beyond our own is observed to be redshifted. The redshift z of a galaxy is the total effect of doppler redshift z_D , cosmological redshift z_c and gravitational redshift z_g (Karttunen et al., 2007).

$$1 + z = (1 + z_D)(1 + z_c)(1 + z_g) \quad (1.27)$$

The doppler redshift z_c is caused by the motion of the galaxy; the cosmological redshift is caused by the expansion of the universe, as originally observed by Hubble in 1929 (Hubble, 2013). Gravitational redshift is caused by the curvature of space-time as described by general relativity. Typically, the effects of doppler redshift and gravitational redshift are negligible and only the galaxy's cosmological redshift needs to be taken into account.

When measuring the stellar kinematics of galaxies, the redshift of the galaxy needs to be taken into account as it would influence the shape of the galactic spectra (how much the spectral lines are shifted).

Line profiles and line broadening: Any spectral line that has been Doppler shifted has a naturally occurring width. This is due to Heisenberg's uncertainty principle, which states that it is impossible to exactly measure the energy and lifetime of a particle's excited state simultaneously. Heisenberg's uncertainty principle is known as:

$$\Delta E \Delta t = \hbar \quad (1.28)$$

where $\hbar$ is Planck's reduced constant. Due to the fundamental uncertainty of an excited particle's energy ΔE , it follows that there is uncertainty in the energy ΔE_γ of the photons that it will radiate during its transition. Consequently, there is uncertainty in the frequency of the photons we measure $\Delta\nu = \frac{\Delta E_\gamma}{h}$. The natural width γ of any spectral line is dependent on both the lifetime of the particle's initial energy state T_i and the lifetime of its final energy state T_f (Karttunen et al., 2007) as:

$$\gamma = \frac{\Delta E_i + \Delta E_f}{\hbar} = \frac{1}{T_i} + \frac{1}{T_f} \quad (1.29)$$

A spectral line may then be further broadened due to the Doppler effect of the particle's (or group of particles') random thermal motion.

The corresponding line profile (intensity vs frequency or wavelength) of a spectral line is defined as (Karttunen et al., 2007):

$$I_\nu = \frac{\gamma}{2\pi} \frac{I_0}{(\nu - \nu_0)^2 + \gamma^2/4} \quad (1.30)$$

where I_0 is the total intensity of the spectral line and ν_0 is the central frequency.

Useful parameters for studying spectral lines are their full width at half maximum (FWHM) and equivalent width W . The resolution of optical telescopes often needs to be adjusted to accurately measure the broadening of spectral lines. Figure 1.12 shows the relationship between the FWHM of a spectral line and its equivalent width W .

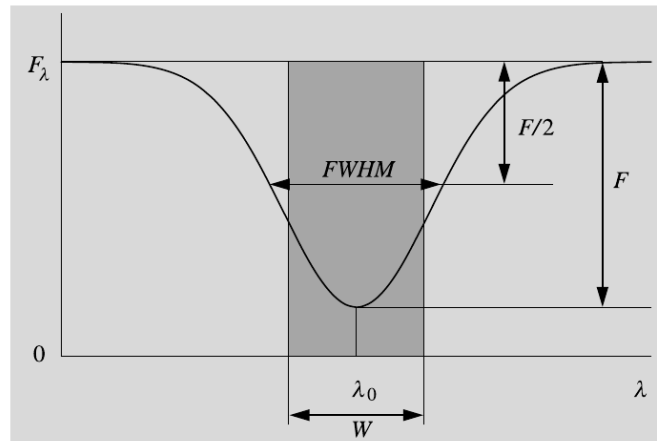


Figure 1.12: Illustration of the FWHM and equivalent width W of a spectral line (Karttunen et al., 2007). The equivalent width of the spectral line is defined such that the spectral line and shaded rectangle have the same area.

Observing stellar spectra: Bringing all these concepts together, we can obtain stellar spectra with an optical spectrograph, as further discussed in section 2.3, with its characteristic (Doppler shifted) continuum and broadened spectral emission and absorption lines. Examples of such stellar spectra are shown in Figure 1.13.

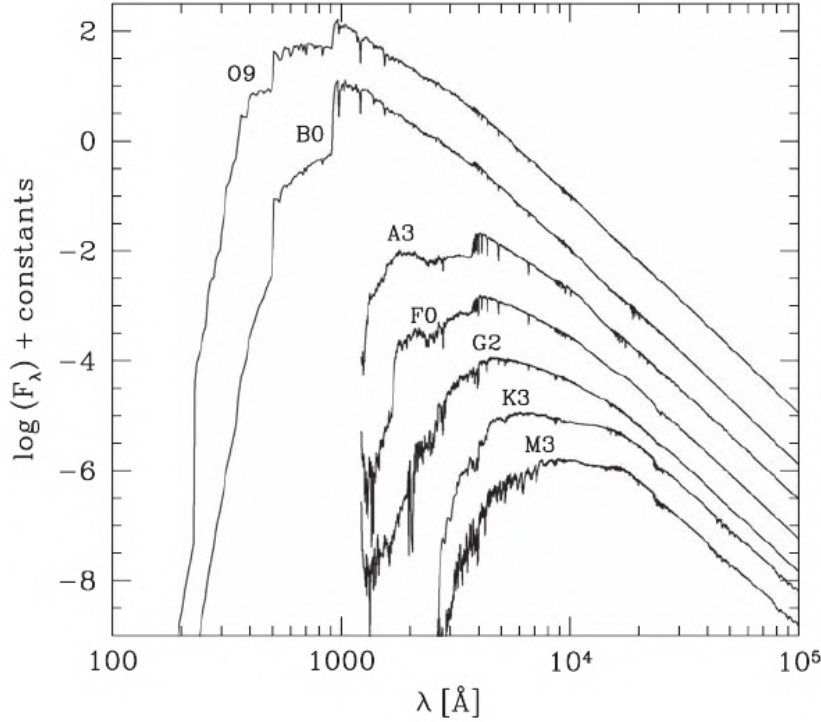


Figure 1.13: Stellar spectra for a variety of stars with different spectral classes, taken from Mo et al. (2010). The stellar spectra are plotted as flux per angstrom F_λ versus wavelength in angstrom. Arbitrary constants were added to each stellar spectra to visualise the spectra together.

As further explained in section 1.4, galaxy spectra are composed out of various stellar spectra. In our study we will use full-spectrum fitting software to fit the galaxy spectra of our sample of galaxies. This software will measure the broadening of the stellar absorption lines on these galaxy spectra, from which we will derive each galaxy's stellar kinematics.

1.3.3 The Initial Mass Function

An essential ingredient for modeling a system's stellar population is its IMF, the initial mass distribution of its main-sequence stars (Matteucci, 2012). Considerable effort has been made to establish the IMF's general form, such as the work of Salpeter (1955), Kroupa (2001) and Davé (2010), but to date there is no clear understanding of the astrophysics

involved that distributes the initial mass of stars (Davé, 2010).

The two most well-known IMFs used in stellar population modeling include the Kroupa IMF and the Salpeter IMF. In our thesis, we will be modeling the stellar populations of our sample of galaxies, listed in Chapter 2.

For our purposes, we will be using both the Kroupa IMF and Salpeter IMF.

The Kroupa IMF: Weidner and Kroupa (2005) argued that the IMF integrated over galaxies could not be the same as the IMF integrated over ordinary star clusters. Such an IMF would need to account for the distribution of stellar remnants and supernovae within these galaxies and take into account the effect of chemical enrichment (Matteucci, 2012). Therefore, a multi-slope IMF, such as the Kroupa IMF, is needed. Kroupa (2001) defines the IMF slopes for galaxies as (Matteucci, 2012):

$$x = \begin{cases} 0.3 & 0.08 \leq m/M_{\odot} \leq 0.50 \\ 1.3 & 0.50 < m/M_{\odot} \leq 1 \\ 1.7 & m/M_{\odot} > 1 \end{cases} \quad (1.31)$$

$$(1.32)$$

$$(1.33)$$

The Salpeter IMF: The first IMF was introduced by Salpeter (1955), which expressed the IMF as a power law function (Matteucci, 2012). The Salpeter IMF is defined over the mass range $0.1 M_{\odot}$ to $100 M_{\odot}$ and is given by equation 1.34.

$$\phi(m) = am^{-(1+x)} \quad (1.34)$$

where $\phi(m)$ is the IMF, a is the normalisation constant obtained by satisfying the condition: $\int_{0.1}^{100} m\phi(m)dm = 1$ and x is the slope of the IMF. Salpeter (1955) defines a single slope IMF with $x = 1.35$.

1.4 Galaxy Spectra and Their Features

In section 1.1, an overview of galaxy evolution was given. In sections 1.2 and 1.3, the two primary research themes of this thesis, namely the stellar kinematics and the stellar populations of galaxies were discussed. Section 1.3 described the various classes of stars and showed a few examples of stellar spectra. In this section, the characteristics of galaxy spectra will be discussed. Furthermore, this section will address how the stellar kinematics and stellar populations of a galaxy can be measured from its spectrum.

The main task of this thesis will be to measure the spatially-resolved stellar kinematics and stellar populations of our sample of galaxies, listed in Chapter 2, using their spectra. Therefore, it is of the utmost importance to understand galaxy spectra and their features.

The baryonic component of galaxies consists of rich stellar populations and various gaseous and dusty components throughout its ISM (Mo et al., 2010). The spectrum of a galaxy is a combination of the spectra of its entire stellar population (with their characteristic absorption lines) and the spectra of its ISM that absorb and re-emit stellar light (Mo et al., 2010). Examples of such spectra are shown in Figure 1.14.

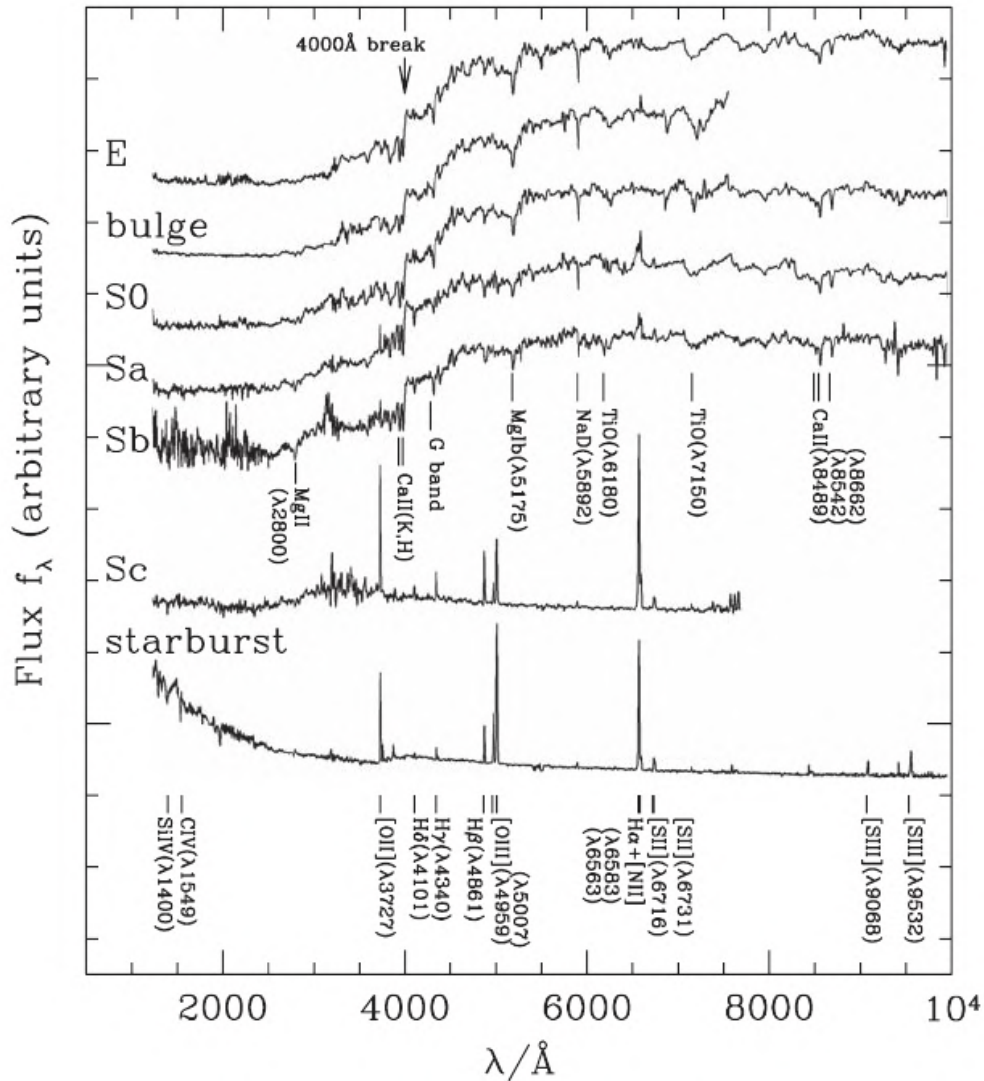


Figure 1.14: Example spectra of a collection of galaxies (Mo et al., 2010). Early-type galaxies tend to be more bright at red and infrared wavelengths due to their older stellar populations. In contrast, late-type galaxies have much younger stellar populations and are more bright at blue and ultraviolet wavelengths.

Early-type galaxies tend to have homogenous spectra with characteristic absorption lines from their old and cool giant stars (Kennicutt Jr, 1992). The differences in absorption features are caused by the varying chemical composition and metallicities of each early-type galaxy's stellar population (Kennicutt Jr, 1992). Late-type galaxies with a morphology of S0, Sa and Sb tend to have quite similar spectra to elliptical galaxies, since their stellar populations are very similar (Kennicutt Jr, 1992). Late-type galaxies with a morphology of Sc and beyond have a much younger stellar population and ongoing stellar activity than E, S0, Sa and Sb galaxies. Therefore, these late-type galaxies have very different spectral features (Kennicutt Jr, 1992). Due to the rich gas content of actively star-forming galaxies, such as Sc galaxies, they are observed to have very strong emission features. These emission features include lines such as: $[SII]$ (9523 Å, 9068 Å, 6731 Å and 6716 Å), $[NII]$ (6583 Å), $H\alpha$ (6563 Å), $[OIII]$ (5007 Å), $H\beta$ (4861 Å), $H\gamma$ (4340 Å), $H\delta$ (4101 Å), $[OII]$ (3727 Å), CIV (1549 Å) and SiV (1400 Å).

1.4.1 Measuring Stellar Kinematics from Galaxy Spectra

In section 1.3.2, the concept of line profiles was introduced. Due to the motion of stars within the galaxy, the line profiles³ associated with the radiation from stars are broadened. By fitting these line profiles and by measuring their broadening, the stellar kinematics of the stars within the galaxy can be derived.

Fitting line profiles as Gaussians: A line profile can be approximated as a Gaussian profile $\mathcal{L}$ with line strength γ (not to be confused with the line width), average rotational velocity V and velocity dispersion σ as free parameters (Van Der Marel and Franx, 1993).

The profile can be expressed as a Gaussian function:

$$\mathcal{L} = \gamma \frac{\alpha(w)}{\sigma} \quad (1.35)$$

where $w \equiv (v - V)\sigma$ and where α is the standard Gaussian given by:

$$\alpha(w) = \frac{1}{\sqrt{2\pi}} e^{-(1/2)w^2} \quad (1.36)$$

Gaussian functions are an excellent low-order approximation for most line profiles (Van Der Marel and Franx, 1993). To determine the deviations from the Gaussian line profile, we generalise the parameters as a sum of orthogonal functions, namely Hermite polynomials (Van Der Marel and Franx, 1993).

³Either emission lines or absorption lines can be considered as “line profiles”, in our case, the stellar absorption lines are considered as the line profiles. Hence, to derive the stellar kinematics of a galaxy, we measure the broadening of the stellar absorption lines on these galaxy spectra, and not the broadening of the stellar emission lines or the gas emission lines.

Hermite polynomials $H_l(y)$ are defined (as originally by Pierre-Simon Laplace) as (Zettili, 2003):

$$H_l(y) = (-1)^l e^{y^2} \frac{d^l}{dy^l} e^{-y^2} \quad (1.37)$$

and satisfy the following condition of orthogonality:

$$\int_{-\infty}^{\infty} H_m(y) H_n(y) e^{-y^2} dy = \sqrt{\pi} \cdot 2^n \cdot n! \delta_{mn} \quad (1.38)$$

where δ_{mn} is the Kronecker-delta function.

$$\delta_{mn} = \begin{cases} 0 & \text{if } m \neq n \\ 1 & \text{if } m = n \end{cases} \quad (1.39)$$

$$(1.40)$$

The first few Hermite polynomials are given by:

- $H_0(y) = 1$
- $H_1(y) = 2y$
- $H_2(y) = 4y^2 - 2$
- $H_3(y) = 8y^3 - 12y$
- and so on following equation 1.37.

Fitting the line-of-sight-velocity-distribution (LOSVD) of a galaxy: Letting $\Sigma(x, y)$ be the line-of-sight projected surface mass density of the stars within the observed galaxy and taking z as the distance along the line-of-sight. The LOSVD of the galaxy is defined as (Mo et al., 2010):

$$\mathcal{L}(x, y, v_z) = \frac{1}{\Sigma(x, y)} \iiint f(\vec{x}, \vec{v}) dv_x dv_y dz \quad (1.41)$$

where $f(\vec{x}, \vec{v})$ is the phase space distribution with cartesian coordinates $\vec{x}$ and corresponding velocities $\vec{v}$. In practice, the LOSVD of a galaxy is fitted with a Gauss-Hermite series (Van Der Marel and Franx, 1993; Mo et al., 2010):

$$\mathcal{L}(v) = [\gamma\alpha(w)/\sigma] \left\{ 1 + \sum_{j=3}^N h_j H_j(w) \right\} \quad w \equiv (v - V)/\sigma \quad (1.42)$$

where h_j are the Gauss-Hermite moments. This allows us to perform a $N+1$ parameter fit to the LOSVD to simultaneously determine the values of the line strength γ , average rotational velocity V , velocity dispersion σ and Gauss-Hermite moments h_3 (skewness) and h_4 (kurtosis) for the galaxy (Mo et al., 2010). The rotational velocity V gives us an indication of the speed at which stars rotate within the galaxy at a particular radius. The velocity dispersion σ gives us a standard deviation measurement of the speed of the stars. Finally, h_3 provides a measure of the galaxy's asymmetry and h_4 provides a measure of the galaxy's symmetric deviations. Elliptical galaxies are naturally less asymmetric than spiral galaxies (Bender et al., 1994).

Measuring the LOSVD of a galaxy with optical spectroscopy: In conclusion, to determine the rotational velocity V , velocity dispersion σ , skewness h_3 and kurtosis h_4 of a galaxy, one simply needs to fit the LOSVD of the galaxy using its spectrum. The spectrum of the galaxy can be obtained by performing an optical spectroscopic study of the galaxy. Conventionally, all the lines on the galaxy spectrum are fitted simultaneously with full-spectrum fitting software. This is the procedure that we will follow in this thesis. The full-spectrum fitting software that we will use to measure the stellar kinematics of our sample of galaxies, pPXF, is discussed in Chapter 2.

1.4.2 Modeling Stellar Populations from Galaxy Spectra

Stellar population synthesis: Stellar population synthesis (SPS) is a well-known technique used by astronomers to study the distribution of ages and metallicities of a given stellar population (Bruzual and Charlot, 2003). The stellar population may either be a simple (singular) stellar population (SSP) or a composite stellar population (CSP) with varying ages and metallicities (Salaris and Cassisi, 2005). SSPs are populations that have formed simultaneously during a quick phase of heightened star-formation activity with similar initial chemical compositions (Salaris and Cassisi, 2005). In contrast, CSPs are populations that have formed at different times with different initial chemical compositions (Salaris and Cassisi, 2005). Examples of SSPs include globular clusters and open clusters. Some elliptical galaxies and some dwarf galaxies are also known to have SSPs (Salaris and Cassisi, 2005). However, most galaxies are known to have CSPs, as they commonly have a complicated star-formation history with several phases of star-formation activity (Salaris and Cassisi, 2005). To model an SSP, one would first need to assume the IMF of the stellar population, such as a Salpeter or Kroupa IMF, as discussed in section 1.3.3. The SSP can then be modeled using an isochrone synthesis technique and a combination of stellar spectra from a trustworthy stellar library (Bruzual and Charlot, 1993). Galaxies are expected to have a composite stellar population (CSP). To model a CSP for a given galaxy spectrum, one would need to first model several SSPs for the galaxy taking into account the galaxy's unique star-formation rates, chemical enrichment rates and dust at-

tenuation. The necessary components of stellar population synthesis is shown in Figure 1.15. This process can be done computationally with full-spectrum fitting software, which is the method we will be using in this thesis. The full-spectrum fitting software that we will use to measure the stellar populations of our sample of galaxies, FIREFLY, is discussed in Chapter 2.

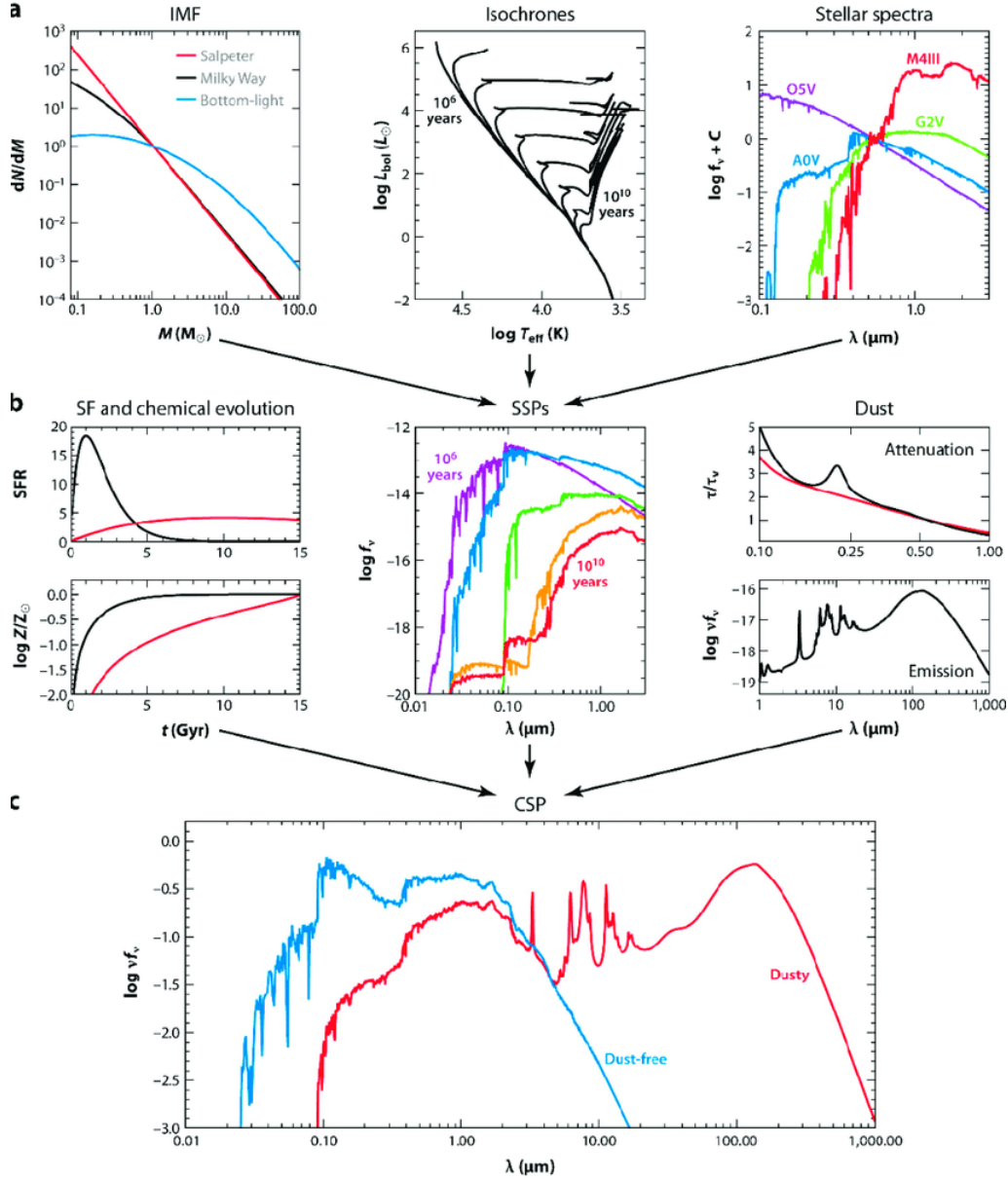


Figure 1.15: Illustration of the necessary components of stellar population synthesis (Conroy, 2013; Leitherer, 2020). (a) An IMF needs to be assumed along with the additional input of stellar isochrones and stellar spectra to model a single stellar population (SSP). (b) Using star-formation and dust-attenuation laws in addition with the model SSP, a composite stellar population (CSP) can be modelled as finally shown in (c).

The limitations of stellar population modeling: The accuracy of any model is dependent on the accuracy of the assumptions made, and stellar population modeling is no different. Stellar population models strongly depend on the stellar library used. As discussed in more detail in section 1.4.3, each stellar library is limited to a certain combination of stellar spectra. As discussed in section 1.4.3, stellar libraries may be either empirical or theoretical, each with their strengths and weaknesses.

Empirical stellar libraries are obtained through observing several stellar spectra. Therefore, the quality of these stellar libraries depend on the quality of the observations made. For instance, the stellar spectra which make up the library are observed with a certain resolution, and within a specific wavelength range. If stellar population modeling is used to fit another observed spectrum, a mismatch in resolution⁴ and wavelength range⁵ is possible. These may influence the accuracy of your results when deriving stellar population properties.

Theoretical stellar libraries consist of a combination of artificially made stellar spectra. These spectra are based on a set of stellar atmospheric parameters. For instance, the stellar spectra which make up the library are hypothetically from stars within a certain range of mass, temperature and chemical abundance. The set of stellar atmospheric parameters may or may not reflect the unique properties of your own observed stellar population. Therefore, caution is advised when deriving stellar population properties with these theoretical stellar libraries. A more in depth understanding of the underlying stellar astrophysics is required when using these libraries.

1.4.3 Stellar Libraries

As previously discussed, stellar population synthesis (SPS) software relies on stellar libraries to derive stellar population properties.

Stellar libraries may be empirical (obtained through observation), theoretical (based on stellar atmospheric models) or a combination of both. Here we present the most commonly used stellar libraries used throughout literature, namely: MILES, STELIB, ELODIE, MARCS and MaStar. These are the same stellar libraries we will use when performing

⁴With “resolution”, we refer to the $R = \lambda/\Delta\lambda$ value of the observations that make up the stellar library. In the case where there is a mismatch in resolution between the stellar library and your own observation’s resolution, corrections are required. These corrections often reduce the quality of fit, influencing the results obtained.

⁵When deriving the stellar population properties of galaxies with stellar population synthesis, the wavelength range of your observation and the stellar library used are very important. Young (blue) stars will radiate at lower wavelengths and older (red) stars will radiate at higher wavelengths. If your wavelength range is too narrow, these stars may be omitted from the modelling process and the age of the stellar population may be completely incorrect when derived.

stellar population modeling for our sample of galaxies.

MILES (2006): The Medium-resolution INT Library of Emperical Spectra (MILES) is a stellar library consisting of 985 synthetic stellar spectra developed for stellar population synthesis (Sánchez-Blázquez et al., 2006). These stellar spectra are based on observations by the 2.5m Isaac Newton Telescope (INT) in the wavelength range of $3525 - 7500 \text{ \AA}$ at a spectral resolution of $2.5 \text{ \AA}$ (FWHM) (Sánchez-Blázquez et al., 2006). This library is available online at <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/402/433#/description>.

ELODIE (2001): The ELODIE empirical stellar library is collection of high-resolution stellar spectra obtained with the ELODIE spectrograph of the 1.93m telescope at the Haute-Provence Observatory (Prugniel and Soubiran, 2001). The library consists of 1962 spectra for 1388 stars in the wavelength range $3900 \text{ \AA}$ to $6800 \text{ \AA}$ (Prugniel and Soubiran, 2001). The stellar atmospheric parameters for this library are (Prugniel and Soubiran, 2001):

- An effective temperature of 3000 K to 60000 K .
- Chemical abundance ratio of $-3.2 \leq [Fe/H] \leq +1.4$

This library is divided into spectra observed at two different resolutions; LH_ELODIE with a resolution of $R = \frac{\lambda}{\Delta\lambda} = 42\,000$ and LL_ELODIE with a resolution of $R = \frac{\lambda}{\Delta\lambda} = 10\,000$ (Prugniel and Soubiran, 2001). This library is available online at http://perso.astrophy.u-bordeaux.fr/~csoubiran/elodie_library.html

STELIB (2003): STELIB is a stellar library consisting of 249 synthetic stellar spectra developed for stellar population synthesis (Le Borgne et al., 2003). These stellar spectra are based on observations by the Jacobus Kaptein Telescope in the wavelength range of $3200 - 9500 \text{ \AA}$ with a spectral resolution of $\lesssim 3 \text{ \AA}$ (Le Borgne et al., 2003). This library is available online at <http://miles.iac.es/>.

MARCS (2008): MARCS is a grid of 10^4 theoretical models of late-type stellar atmospheres (Gustafsson et al., 2008). These stellar atmospheres span various masses and radii and satisfy the following conditions:

- Each stellar atmosphere has an effective temperature between 2500K and 8000K .
- Their chemical abundance ratios satisfy: $-5 \leq [Me/H] \leq +1$ and $[\alpha/Fe] = 0$

These theoretical models can further be used to generate synthetic stellar spectra for stellar population synthesis (Gustafsson et al., 2008). This library is available online at <https://marcs.astro.uu.se/>.

MaStar (2019): MaStar is the most comprehensive empirical stellar library to date (Yan et al., 2019). The library contains over 10 000 stellar spectra observed in the wavelength range 3 622 Å to 10 354 Å with the 2.5m telescope at the Apache Point Observatory at a resolution of 1800 Å (Yan et al., 2019). In comparison with previous stellar libraries, MaSTAR has the widest wavelength coverage and largest sample of empirical stellar spectra.

A comparison between the empirical stellar libraries (all the libraries except MARCS) is provided in Table 1.3 below:

Table 1.3: Comparison of current empirical stellar libraries (Yan et al., 2019)

Stellar library	Number of stellar spectra	Wavelength range (Å)
MILES (2006)	985	3525 – 7500
STELIB (2003)	249	3200 – 9500
ELODIE (2001)	1388	4100 – 6800
MaSTAR (2019)	> 10 000	3622 – 10 354

1.5 Research Motivation and Objectives

In this thesis, our research objectives are measuring the spatially-resolved stellar kinematics and stellar populations of our sample of galaxies. These galaxies include a sample of 18 of the Complete Local-Volume Groups Sample (CLoGS) Brightest Group Early-Type Galaxies (BGEs), and the MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects - Observing Southern Emitters) galaxy HIPASS-J1153-28 (J1153). The motivations for studying the CLoGS BGEs and the MHONGOOSE galaxy J1153 are given in sections 1.5.1 and 1.5.2. Finally, the research objectives are described in further detail in section 1.5.3.

1.5.1 The Importance of Studying the Complete Local-Volume Groups Sample (CLoGS) Brightest Group Early-Type Galaxies (BGEs)

In this section, we discuss the importance of studying BGEs and the significance of CLoGS. We motivate why the stellar kinematics and stellar populations of these galaxies are worth studying.

The importance of studying galaxy groups: According to Tully (1987) and Eke et al. (2006), galaxy groups within the local Universe contain over 60% of all observable galaxies. Furthermore, galaxy groups host the majority of both baryonic and dark matter content in the Universe (Fukugita et al., 1998). Therefore, galaxy groups in the local Universe are excellent laboratories for studying galaxy evolution and for improving our understanding of dark matter.

To date, the distinction between galaxy groups and galaxy clusters has been arbitrary and there is no clear understanding of the exact difference between these environments (Mo et al., 2010). Galaxy groups have been considered as scaled down versions of clusters, smaller in scale and containing fewer member galaxies; however the physics between these environments are not necessarily the same (Mo et al., 2010). In fact, galaxy groups have been found to be more complex than previously thought, and more than just an intermediate environment between individual galaxies and galaxy clusters (Oppenheimer et al., 2021). In this thesis, we hope to learn more about galaxy groups, BGEs and their unique evolutionary processes.

The importance of studying the stellar kinematics and stellar populations of BGEs: The most massive galaxies within group environments may have a mass between $\sim 10^{11} M_{\odot}$ and $\sim 10^{13} M_{\odot}$ (Sparke and Gallagher III, 2007). The dominant central galaxy in each group may either be early-type or late-type. Of interest to this thesis are the CLoGS BGEs. BGEs typically reside close to the centres of their groups (close to the centre of each group’s X-ray halo and dark matter distribution) and are some of the most luminous galaxies that can be found in group environments (Jones and Forman, 1984).

BGEs are believed to be some of the earliest galaxies to have formed within the group environment, possibly before the existence of the group itself, via the previous merging of disc galaxies and their dark matter haloes (Toomre and Toomre, 1972). Due to the enormous gravitational potential of BGEs, the evolution of BGEs is closely tied to the evolution of its group environment. By measuring the stellar kinematics of BGEs, we can indirectly study the dark matter content of these galaxies. Ultimately, through our observations, we hope to provide more data to those conducting cosmological simulations of group and cluster environments, such as Marini et al. (2021) and Jung et al. (2022). By improving the accuracy of these simulations, we can better constrain the physical properties of group environments, such as their hydrodynamics and dark matter content.

The BGE within each group is often red in colour and believed to have little to no on-going star-formation. However, these so-called “red and dead” galaxies may have some unexpected star-formation and young stellar populations (Romeo et al., 2008). The mechanisms that drive this unexpected star-formation is still poorly understood, as there exists a complicated relationship between the star-formation of these galaxies and the amount of

cold gas present in the intra-group medium (IGM) of their groups (Janowiecki et al., 2017). The processes that may influence the star-formation rates of these galaxies may either be internal (secular - caused by the galaxy itself) or external (caused by the group environment). Some internal processes include AGN-feedback, in which the heating and expulsion of gas quench star-formation (Di Matteo et al., 2005; Fabian, 2012). External processes may include cooling from the IGM, galaxy-environment interaction such as RAM-pressure stripping and galaxy-galaxy interactions such as tidal stripping and merging (Fakhouri et al., 2010; Banks et al., 2021; Loubser et al., 2022). Recent studies concerning the star-formation and gas content of BGEs include that of Kolokythas et al. (2022), who used the CLoGS sample of nearby galaxy groups. In this thesis, we will further investigate the stellar populations of a sub-sample of CLoGS BGEs. We hope to discover possible links between the known multi-wavelength properties of the CLoGS BGEs and their stellar population properties. This will provide insight to how stars may form within these unique environments.

The significance of the Complete Local-Volume Groups Sample (CLoGS):

CLoGS is a sample of 53 optically selected galaxy groups within the local volume (within 80 Mpc) (O’Sullivan et al., 2017). These groups are divided into either the high-richness (HRS) sub-sample or the low-richness (LRS) sub-sample based on their richness parameter ‘R’, where ‘R’ is the number of optically bright galaxies with a luminosity of $\log(L_B) \geq 10.2 L_\odot$ (O’Sullivan et al., 2017). In further detail, the HRS sub-sample are groups with $4 \leq R \leq 8$ (26 of the 53 groups) and the LRS sub-sample are groups with $R = 2$ or $R = 3$ (27 of the 53 groups) (O’Sullivan et al., 2017).

Most galaxy group surveys rely on either X-ray or optical selection, yet these methods are prone to certain mistakes. Some galaxy groups possess extensive X-ray haloes due to the thermal radiation of plasma in its group environment; therefore, X-ray selection is ideal for detecting such fully virialised groups (Marinoni and Hudson, 2002). However, it is found that X-ray selection is biased towards the detection of cool-core (CC) groups, groups with a low central entropy and temperature (Eckert et al., 2018). When using the alternative of optical selection, galaxies may superimpose along the same line of sight, may be too faint to identify or may vary significantly in brightness before becoming fully virialised (O’Sullivan et al., 2017). Optical selection is especially difficult since most groups only contain a handful of optically bright galaxies. To prevent these problems, CLoGS firstly selects groups optically, avoiding the bias of X-ray selection towards CC systems and then performs a follow-up X-ray study to determine the halo properties of these groups to further prevent false detection O’Sullivan et al. (2017).

CLoGS further selects groups based on the following criteria (O’Sullivan et al., 2017):

- Each group must have a minimum of four member galaxies.

- Each group must at least have one early type galaxy with an optical luminosity of $L_B \geq 3 \times 10^{10} L_\odot$.
- Each group must be visible to the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT) for further study (the groups must have a declination of $\delta > -30^\circ$ to be visible to these telescopes).
- The dominant galaxy within each group is an early-type galaxy (BGE).

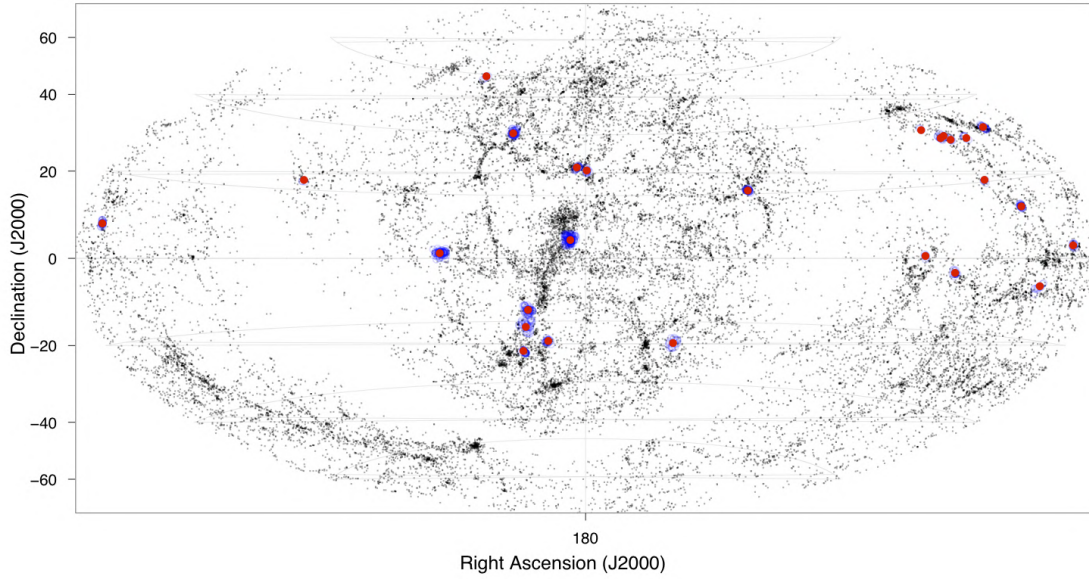


Figure 1.16: The coordinates of the CLoGS sample. The dominant ellipticals are shown in red, the member galaxies are shown in blue and the remaining galaxies are shown in black. Image credit: https://www.sr.bham.ac.uk/~ejos/CLoGS_Sample.html

To date, CLoGS has been studied for about a decade and significant progress has been made in understanding the HRS sub-sample’s environmental X-ray properties (O’Sullivan et al., 2017). Furthermore, the radio properties of both the HRS sub-sample’s and LRS sub-sample’s central radio galaxies have been studied in detail (Kolokythas et al., 2018; Kolokythas et al., 2019). More recently, Loubser et al. (2018) studied the stellar velocity dispersion profiles of 55 central galaxies. 32 of these are brightest cluster galaxies (BCGs) observed with HET. The remaining 23 are BGEs from the CLoGS group sample (Loubser et al., 2018). A large diversity of velocity dispersion profiles was found; however, not all 53 BGEs of the CLoGS group sample have been studied yet. Therefore, for completeness sake, we study the spatially-resolved stellar kinematics of a sub-sample of 18 CLoGS BGEs with the Southern African Large Telescope (SALT). The stellar populations of these 18 CLoGS BGEs are unknown and will therefore be additionally studied in this thesis. This will complement existing multiwavelength studies of these galaxies, such as by O’Sullivan et al. (2018a) and Kolokythas et al. (2022).

1.5.2 The Importance of Studying the MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects - Observing Southern Emitters) Galaxy HIPASS-J1153-28

MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects - Observing Southern Emitters) is the first ever deep survey of nearby galaxies to probe the very low-column density of neutral hydrogen (HI) below 10^{18} cm^{-2} (De Blok et al., 2017). MHONGOOSE consists of a sample of 30 nearby disk and dwarf galaxies with a luminosity of $\sim 12 \leq M_R \leq 22$ with a substantial HI mass between the order of $\sim 10^6 M_\odot$ and $\sim 10^{11} M_\odot$ (De Blok et al., 2017). MHONGOOSE will be the foremost survey of the neutral gas content of nearby galaxies and a precursor to future surveys to be done with the upcoming Square Kilometer Array (SKA) (De Blok et al., 2017). The MHONGOOSE survey is relatively new and some early results have recently been presented, such as the early observations of 18 of the MHONGOOSE galaxies by Sorgho et al. (2019) and the analysis of the low column density HI environment of 20 of the MHONGOOSE galaxies by Sardone et al. (2021a) with MeerKAT. These studies hope to establish star-formation laws in these uniquely dense HI environments. Optical spectroscopic studies of these galaxies with the Southern African Large Telescope (SALT) will complement ongoing studies. Therefore, in this thesis, we study the spatially-resolved stellar kinematics and stellar populations of a HIPASSJ1153-28, for which we have some existing information.

1.5.3 Research Objectives

To summarise our research objectives, we aim to measure the spatially-resolved stellar kinematics and stellar population properties of our subsample of 18 CLoGS BGEs, as well as the MHONGOOSE galaxy J1153, as described in sections 2.1 and 2.2 respectively. The Southern African Large Telescope (SALT) Robert Stobie Spectrograph (RSS) has been used to obtain optical spectra for these galaxies. These spectra will be fitted with full-spectrum fitting software to derive their spatially-resolved stellar kinematics and stellar population properties. A detailed description of the SALT spectroscopic observations and data reduction is provided in Chapter 2. Chapter 2 concludes with a description of the full-spectrum fitting software pPXF and FIREFLY (see sections 2.5 and 2.6), which will be used to accomplish our research objectives.

Firstly, the stellar kinematic properties of the CLoGS BGEs will be compared to other complimentary samples of galaxies, such as field early-type galaxies (ETGs) and brightest cluster galaxies (BCGs). Such comparisons will show how the CLoGS BGEs are unique as a class of galaxy, and highlight the astrophysical difference between the different environments of these galaxies. For instance, the evolutionary difference between brightest group galaxies and brightest cluster galaxies and the environmental difference between groups

and clusters. Additionally, it will be tested whether some of the latest galaxy evolution simulations can replicate the stellar kinematic properties which we observe for the CLoGS BGEs. This test will reveal the possible shortcomings of these simulations and how these simulations could be improved. Ultimately, this will improve our understanding of the unique environmental properties of galaxy groups and the evolution of brightest group early-type galaxies.

Secondly, the stellar population properties of the CLoGS BGEs will be compared against the existing multi-wavelength information available for these galaxies. In more detail, the inner and outer stellar population ages of these galaxies will be compared against the radio properties, X-ray properties, star formation rates and cold gas content of these galaxies. We hope to derive potential astrophysical explanations for the unique spatially resolved stellar populations ages which we observe. For instance, how AGN and star formation activity may influence the stellar population ages observed for the inner and outer regions of each CLoGS BGE. Furthermore, how the cold gas content may relate to the stellar population ages observed in the inner and outer regions of each CLoGS BGE.

Finally, the stellar kinematic and stellar population properties of the MHONGOOSE galaxy J1153 will similarly be compared to existing multi-wavelength information available for this galaxy. We hope to prove that similar spectroscopic techniques can be used for analysing the spatially resolved stellar kinematic and stellar population properties of a faint dwarf spiral galaxy such as J1153. The study of J1153 can be seen as a “proof of concept” for further studying the MHONGOOSE sample of galaxies. Similarly, we hope to derive a potential astrophysical explanation for the spatially resolved stellar population ages which we observe for J1153. For instance, a link between the cold gas content and the stellar population ages of the different regions of J1153.

Chapter 2

SALT Spectroscopic Observations and Data Reduction

“Astronomy is useful because it raises us above ourselves. It is useful because it is grand. It shows us how small is man’s body, how great his mind. Since his intelligence can embrace the whole dazzling immensity where his body is only an obscure point. And enjoy its silent harmony.”

Henri Poincaré

This chapter describes our data sample of galaxies and the data reduction process using the Southern African Large Telescope (SALT) Robert Stobie Spectrograph (RSS). Furthermore, this chapter discusses how the spatially-resolved stellar kinematics and stellar populations of these galaxies were measured using the full-spectrum fitting software pPXF by Cappellari (2017) and FIREFLY by Wilkinson et al. (2017).

2.1 The CLoGS BGEs

The majority of the galaxies that we have studied are a sample of 18 of the CLoGS BGEs as previously discussed in section 1.5.1. These galaxies are the primary theme of this thesis.

The New General Catalog (NGC) names of the BGEs, their redshift, z , distance in megaparsec, D , average central velocity dispersion, σ_{avg} , effective radius in kiloparsec, R_e , CLoGS sub-sample (HRS or LRS, as discussed in section 1.5.1), their corresponding Lyons Groups of Galaxies (LGG) group name and their J2000 coordinates (right ascension, α , and declination, δ) are shown in Table 2.1.

Table 2.1: CLoGS BGEs sub-sample (and other galaxies of interest). The value and error for each galaxy’s σ_{avg} , are the average and standard deviation of the central velocity dispersion measurements available from literature according to the HYPERLEDA database (Paturel et al., 2003). Each galaxy’s effective radius, R_e , is the median of the Two Micron All Sky Survey (2MASS) effective radii, as measured in the j ($1.235 \mu\text{m}$), h ($1.662 \mu\text{m}$) and k ($2.159 \mu\text{m}$) bands (Skrutskie et al., 2006).

Name	z	D (Mpc)	σ_{avg}	R_e (kpc)	Group	Sub-sample	α (J2000)	δ (J2000)
ESO 507-25	0.011	45	245.2 ± 8.9	3.33	LGG310	HRS	12 : 51 : 31.85	−26 : 27 : 07.70
NGC 128	0.013	60	211.1 ± 51.8	2.89	LGG006	LRS	00 : 29 : 15.07	02 : 51 : 50.60
NGC 193	0.015	74	200.9 ± 0.4	3.39	LGG009	HRS	00 : 39 : 18.58	03 : 19 : 52.90
NGC 1395	0.006	21	256.3 ± 25.2	3.02	LGG097	LRS	03 : 38 : 29.79	−23 : 01 : 39.70
NGC 1550	0.012	53	305.7 ± 13.8	2.90	LGG133	LRS	04 : 19 : 37.92	02 : 24 : 35.60
NGC 2292	0.007	30	142.0 ± 3	-	LGG138	LRS	06 : 47 : 39.80	−26 : 44 : 46.00
NGC 2911	0.011	45	234.0 ± 20.3	4.25	LGG177	LRS	09 : 33 : 46.10	10 : 09 : 08.90
NGC 3078	0.009	34	249.0 ± 19.6	2.81	LGG185	HRS	09 : 58 : 24.60	−26 : 55 : 35.90
NGC 3325	0.019	80	169.0 ± 0	3.45	LGG205	LRS	10 : 39 : 20.46	−00 : 12 : 01.00
NGC 3923	0.006	20	246.4 ± 25.2	5.40	LGG255	LRS	11 : 51 : 01.78	−28 : 48 : 22.40
NGC 4697	0.004	18	177.1 ± 24.9	3.98	LGG314	LRS	12 : 48 : 35.90	−05 : 48 : 02.50
NGC 5044	0.009	38	240.0 ± 16.7	5.09	LGG338	HRS	13 : 15 : 23.97	−16 : 23 : 08.00
NGC 5061	0.007	28	197.0 ± 8.8	3.12	LGG341	LRS	13 : 18 : 05.05	−26 : 50 : 14.00
NGC 5084	0.006	23	211.8 ± 12.4	3.75	LGG345	HRS	13 : 20 : 16.92	−21 : 49 : 39.30
NGC 5153	0.014	60	183.2 ± 4.9	3.13	LGG351	HRS	13 : 27 : 54.33	−29 : 37 : 04.90
NGC 5903	0.009	36	213.3 ± 13.4	3.86	LGG398	LRS	15 : 18 : 36.53	−24 : 04 : 06.90
NGC 7252	0.016	66	150.0 ± 27.0	2.79	LGG457	LRS	22 : 20 : 44.78	−24 : 40 : 41.90
NGC 7377	0.011	46	164.6 ± 19.4	4.82	LGG463	LRS	22 : 47 : 47.51	−22 : 18 : 43.50
NGC 2293	0.0068	30	264.2 ± 14.2	4.45	LGG138	LRS	06 : 47 : 42.91	−26 : 45 : 15.7
NGC 5152	0.0144	60	-	-	LGG351	HRS	13 : 27 : 51.12	−29 : 37 : 07.0

The effective radii of the CLoGS BGEs listed in Table 2.1 are calculated as:

$$R_e = \text{median}(j_r_eff, h_r_eff, k_r_eff) \sqrt{\text{sup_ba}} \quad (2.1)$$

where `sup_ba` is the minor-to-major axis ratio measured at the 3σ isophote for each 3-band co-added image of the 2MASS survey (Skrutskie et al., 2006). Per definition, R_e is the radius at which half of the galaxy’s total flux is contained (Ferreras, 2019). For elliptical galaxies, R_e is defined along the major axis of the galaxy. R_e is a convenient physical parameter to use for further analysis. The stellar kinematics and stellar populations of the CLoGS BGEs will later be studied with regard to their effective radius. This will be further discussed in Chapter 3. In addition to the 18 CLoGS BGEs listed in Table 2.1, we study two additional galaxies, namely NGC 2293 and NGC 5152. NGC 2293 is a nearby neighbouring galaxy of NGC 2292, and NGC 5153 is a nearby neighbouring galaxy

of NGC 5152. Due to the close proximity of NGC 2293 with NGC 2292, they will soon merge (on a cosmological time scale). Furthermore, NGC 2293 may influence NGC 2292’s stellar kinematics due to the strong gravitational pull between these two galaxies. The same can be said for NGC 5152 and NGC 5153. Therefore, when studying NGC 2292 and NGC 5153, the influence of their nearest neighbour will be kept in mind.

For the 18 CLoGS BGEs, including NGC 2293 and NGC 5152, we perform optical spectroscopic observations with the Southern African Large Telescope (SALT) Robert Stobie Spectrograph (RSS). The finding charts of these galaxies are shown in Appendix A. For each galaxy and slit placement, we perform one observation to measure their spectra, using the PG0900 (low-resolution) grating of the SALT RSS. More details about the SALT RSS are given in section 2.3

2.2 The MHONGOOSE Galaxy HIPASSJ1153-28

The methods used to measure the stellar kinematics and stellar populations of the CLoGS BGEs can similarly be used to measure other galaxies of interest, for instance HIPASSJ1153-28 (J1153, also known as UGCA 250), a nearby dwarf spiral galaxy, rich in HI and part of the ongoing MHONGOOSE survey (De Blok et al., 2017). We study J1153 to complement new results from the ongoing MHONGOOSE survey, such as Sardone et al. (2021a). J1153 is located 30.19 ± 2.14 megaparsec away at $\alpha = 11 : 53 : 24.06$ and $\delta = -28 : 33 : 11.4$ with a redshift of $z = 0.00569$ (Paturel et al., 2003). J1153 is faint and difficult to observe in comparison with the CLoGS BGEs; therefore, for J1153, we perform several different optical spectroscopic observations with various axis orientations and resolutions. The use of flat fields was also experimented with. These observations are summarised in Table 2.2.

Table 2.2: Observations of J1153. The ‘Axis’ column indicates along which axis the galaxy was observed. It is further shown which SALT RSS grating was used and whether or not flat fielding was used.

Observation name	SALT RSS Grating	Resolution	Axis	Flat Fielding
J1153_LR_Majv1	PG0900	Low	Major	No
J1153_LR_Min	PG0900	Low	Minor	No
J1153_LR_Min_fl	PG0900	Low	Minor	Yes
J1153_LRv2_Majv1	PG0900	Low	Major	No
J1153_MR_Maj	PG1300	Medium	Major	No
J1153_MR_Maj_fl	PG1300	Medium	Major	Yes
J1153_MR_Min	PG1300	Medium	Minor	No

In this thesis, we will experiment with combining some of these observations (of similar

axis and resolution). This is done to test whether or not a better signal-to-noise ratio could be gained.

The SALT RSS data reduction is an intricate process, involving several steps and corrections. In section 2.3, we provide an overview of the SALT RSS, and in section 2.4, a detailed summary of the data reduction process (SALT RSS pipeline) is provided.

2.3 Optical Spectroscopy with the Southern African Large Telescope (SALT) Robert Stobie Spectrograph (RSS)



Figure 2.1: The Southern African Large Telescope in Sutherland, Northern Cape, South Africa Image credit: <https://www.salt.ac.za/galleries/photo-gallery/>

The Southern African Large Telescope (SALT) is a 10-m class telescope similar in design to HET at McDonald Observatory, Texas (Stobie et al., 2000). The telescope is primarily designed for optical and infrared spectroscopy and is equipped with three spectrographs, namely the High Resolution Spectrograph (HRS), Integral Field Unit (IFU) and Robert-Stobie Spectrograph (RSS) (Stobie et al., 2000). As previously mentioned, data for this study was obtained with the RSS.

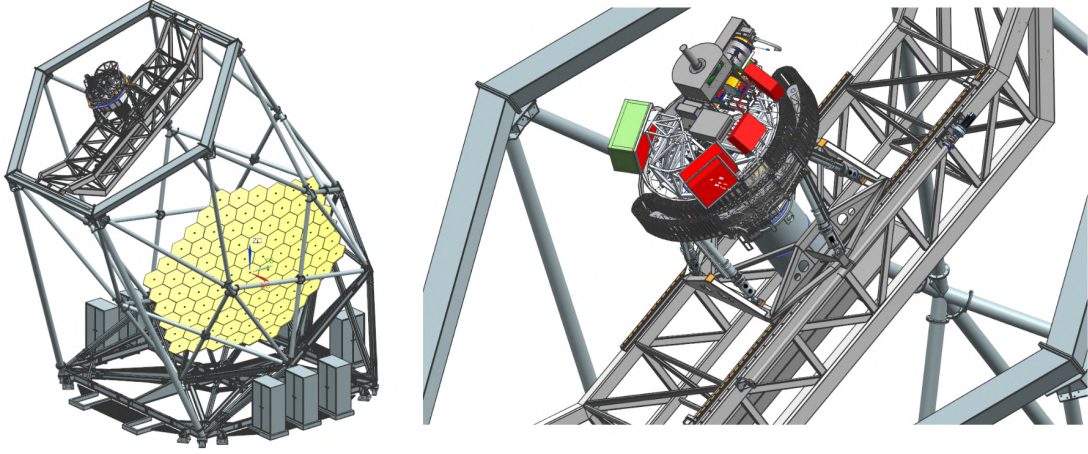


Figure 2.2: Left: The internal structure of the SALT telescope. Right: Zoomed in image of the telescope's tracker and instruments. At the very top sits the RSS spectrograph. Image credit: https://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html#h.i157iczab4n2

The RSS covers the wavelength range of 3200 Å to 9000 Å (Buckley et al., 2005). The CCDs for the RSS are E2V CCD 44-82 chips, each with a pixel size of $2k \times 4k \times 15 \mu m$ (O'Donoghue et al., 2004). The RSS has various observation modes, for instance the slit width and diffraction grating can be changed to observe astronomical objects at different resolutions. For our research purposes, the slit-width of the RSS was set to $1.5''$ and the grating set to one of three different configurations, depending on the resolution required for the observation. These three grating configurations are: PG0900, with a camera angle of $\sim 31.75^\circ$ and grating angle of $\sim 15.875^\circ$; PG1300, with a camera angle of $\sim 51.25^\circ$ and grating angle of $\sim 25.625^\circ$; and PG2300, with a camera angle of $\sim 81.25^\circ$ and grating angle of $\sim 40.625^\circ$ (Burgh and Nordsieck, 2017). The wavelength ranges and resolution of each grating are shown in Table 2.3.

Table 2.3: Wavelength range and resolution of the three grating configurations for the SALT RSS (Burgh and Nordsieck, 2017). The chip gaps are due to the physical spacing between the telescope's CCDs. The resolution 'R' is defined as $R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is the Full-Width-Half-Maximum (FWHM) of the observation.

Grating	Wavelength Range	Blue Chip Gap	Red Chip Gap	Resolution 'R'
PG0900	4486.3 Å – 7533.1 Å	5487.4 Å – 5543.5 Å	6531.6 Å – 6586.1 Å	(Low) 879 – 1245
PG1300	5620 Å – 7607.1 Å	6285.2 Å – 6322.1 Å	6966.4 Å – 7001.6 Å	(Mid) 1609 – 1976
PG2300	5150.4 Å – 6094.8 Å	5477.6 Å – 5495.5 Å	5801.7 Å – 5818.2 Å	(High) 3024 – 3391

As previously discussed in sections 2.1 and 2.2, we use the PG0900 grating for all CLoGS BGE observations and both the PG0900 and PG1300 grating when performing multiple observations for J1153.

2.4 The SALT RSS Spectroscopy Pipeline

The purpose of the data reduction process is to extract usable galaxy spectra from the raw FITS (Flexible Image Transport System) file images of the galaxies measured with the Southern African Large Telescope Robert Stobie Spectrograph (SALT RSS). These FITS files contain the photon count corresponding to each pixel, as measured by the telescope’s charged coupled devices (CCDs) and information about the observation itself in a “header” menu (Wells and Greisen, 1979). An example of one of these FITS files is shown in Figure 2.3

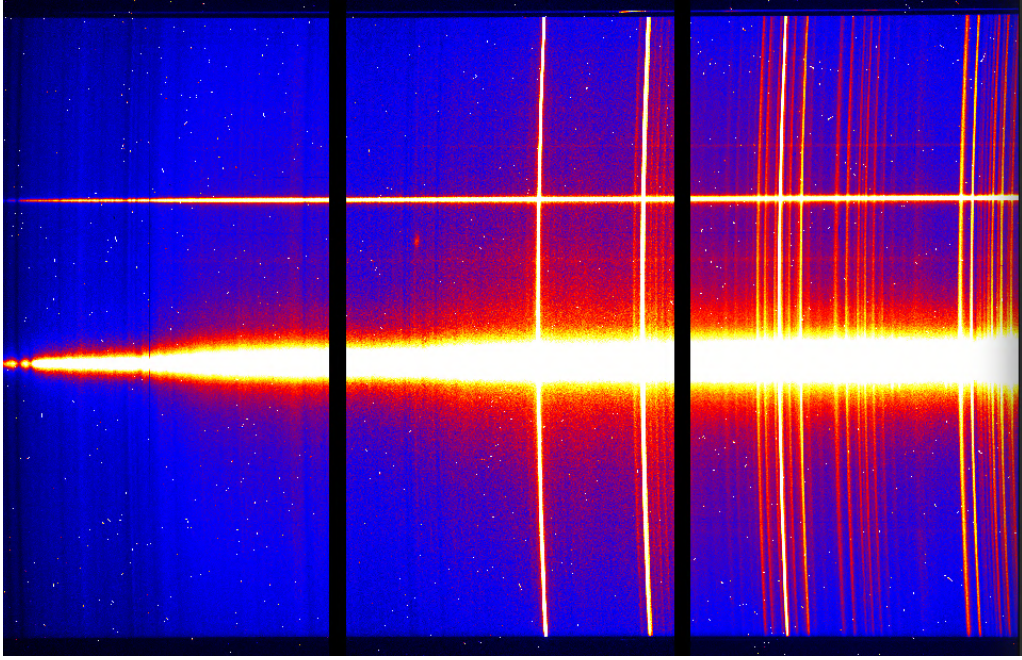


Figure 2.3: Raw spectroscopic data of ESO 507-25. The image is noticeably contaminated by cosmic rays and telluric (atmospheric) lines. The cosmic rays are shown by overexposed pixels in white and the telluric lines are shown by the curved vertical lines over the image. The image also contains unnecessary background information, such as a background star shown by a horizontal line above the galaxy’s spectroscopic data.

As shown in Figure 2.3, the spectroscopic data is affected by atmospheric extinction as well as telluric contamination - meaning that the earth’s atmosphere absorbs and re-emits certain wavelengths of radiation and distorts the image. The data reduction pipeline corrects for these effects. The entire data reduction procedure (for a single observation) can be completed in 14 steps and is summarised in Figure 2.4. The data reduction is based on the pipeline presented in Ramphul (2018), which is a well-established method for reducing SALT RSS data. Ramphul (2018)’s pipeline is publicly available at: https://github.com/rajin/rajin_code. We use Ramphul (2018)’s pipeline to complete the first nine steps of our data reduction process. For the remaining five steps, in which unique corrections

need to be made, novel Python code is used to complete the data reduction process. The Python code is based on the general SALT RSS Long-slit data reduction guide, available here: http://mips.as.arizona.edu/~khainline/salt_redux.html#. The code written for this thesis is listed in Appendix B.

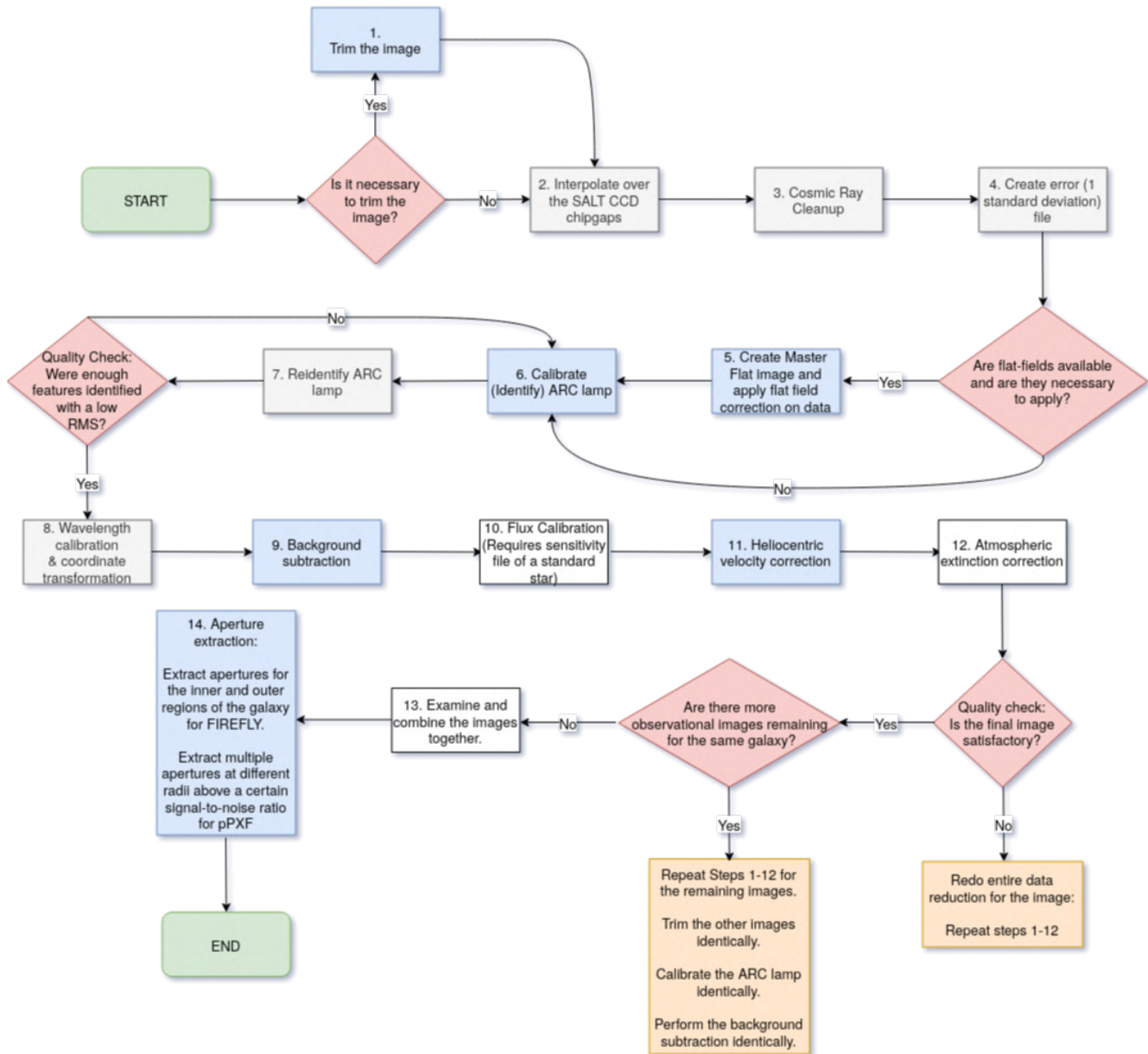


Figure 2.4: Our SALT RSS Spectroscopy Pipeline. Based on Ramphul (2018) and the general SALT RSS Long-slit data reduction guide. Steps that are performed automatically are indicated by the white blocks and steps that require user input are indicated by the blue blocks. Conditions and quality checks are indicated by the red diamonds and instructions are indicated by the yellow blocks.

To complete the data reduction process for our data sample of galaxies, a programming environment was created with the following packages installed: Python 2.7.15, IRAF/PyRAF 2.1.15 and PySALT 0.50. More about the IRAF and PySALT data reduction environments can be read in Tody (1986) and Crawford et al. (2010), respectively. A detailed explanation of all 14 data reduction steps is given in the rest of this section:

1. Trim the image: Trimming the image is the first essential step in the data reduction process. Not only does trimming conserve disc space by getting rid of unnecessary information, but also ensures that the wavelength calibration (Step 8) is applied optimally. Each image needs to be trimmed with the galaxy’s data at the centre and with a sufficient amount of background data such that background subtraction (Step 9) can be applied.

2. Interpolate over the SALT CCD chipgaps: There are gaps in the spectroscopic data due to the physical gaps of the telescope’s CCDs, as shown in Figure 2.3. These gaps need to be linearly interpolated over to maximise the amount of usable data and to ease the full-spectrum fitting process for pPXF and FIREFLY. pPXF and FIREFLY are explained in section 2.5 and 2.6 respectively. See Ramphul (2018) for further details on the interpolation.

3. Cosmic ray cleanup: Each observation of each galaxy has an exposure time of ~ 1000 s, during this time cosmic rays are detected by several random CCD pixels. These pixels are cleaned up with IRAF’s L.A.Cosmic task, according to Ramphul (2018).

4. Create error (1 standard deviation) file: To obtain a formal error on our results when later using FIREFLY, as explained in section 2.6.2, a 1 standard deviation error image is required. It is assumed that the noise is Poissonian and the error on each pixel is calculated as, according to Ramphul (2018):

$$\text{poissonian noise} = \sqrt{\text{science frame value} + \text{average read noise}^2} \quad (2.2)$$

5. Create master flat image and apply flat field correction to data: The pipeline of Ramphul (2018) includes the option of flat field correction. For our CLoGS BGE observations, we achieved a high enough signal-to-noise ratio and decided that flat field corrections would be unnecessary. However, for the MHONGOOSE galaxy J1153, we experiment with flat fields and apply this step when necessary.

6. Calibrate (identify) ARC lamp: Arguably the most important step in the entire data reduction process is the identification of each observation’s ARC lamp’s spectral features. By identifying these spectral features and specifying their wavelengths, we can apply the wavelength calibration and coordinate transformation (Step 8) on the science frame of the galaxy’s image. This is done with the `NOAO.TWODSPEC.LONGSLIT.IDENTIFY()` command in IRAF. It is crucial to identify as many spectral features as possible, as accurately as possible. The spectral features we identified for our PG0900, PG1300 and PG2300 data is shown in Figures C.1, C.2 and C.3 respectively in Appendix C. Each observation is unique, and therefore these solutions can’t be universally implied. As a general rule of thumb we identified as many spectral features such that the root-mean-square-error (RMSE) was less than 0.5.

7. Reidentify ARC lamp: After the manual identification of several of the ARC lamp’s spectral features, IRAF will attempt to identify the possible remaining features automatically with the `NOAO.TWODSPEC.LONGSLIT.REIDENTIFY()` command. This is done for each line in the spatial direction of the 2D frame. This should dramatically increase the number of spectral features identified. To ensure accuracy, we set the maximum number of features that can be lost by `REIDENTIFY()` to 5. If `REIDENTIFY()` lost too many spectral features, the solution was deemed inaccurate and the data reduction for the image needed to be repeated with a different combination of manually identified spectral features.

8. Wavelength calibration and coordinate transformation: The spectroscopic data measured by the CCDs is distorted by the Earth’s atmosphere. The data can be corrected by the `NOAO.TWODSPEC.LONGSLIT.FITCOORDS()` and `NOAO.TWODSPEC.LONGSLIT.TRANSFORM()` IRAF commands. The `FITCOORDS()` command fits a 6th order Chebyshev function to the telluric lines stretching across the data and the `TRANSFORM()` command transforms these distorted lines into straight lines. `TRANSFORM()` also transforms the x-axis pixel coordinates into wavelength in angstroms (Ramphul, 2018).

9. Background subtraction: With the telluric lines now straightened, they can be removed from the image with the `NOAO.TWODSPEC.LONGSLIT.BACKGROUND()` IRAF command. This procedure is described in detail in Ramphul (2018).

10. Flux calibration: The SALT telescope’s pupil; the view of the mirror from the tracker moves during each observation, as shown in Figure 2.5 (Crawford et al., 2010). This causes the effective collection area of the telescope to change during each observation. Therefore, absolute flux measurements cannot be obtained with SALT due to its design. To correct for this, spectrophotometric standards, standard stars with a known

flux, are observed and made available to perform relative flux calibrations for other observed sources.

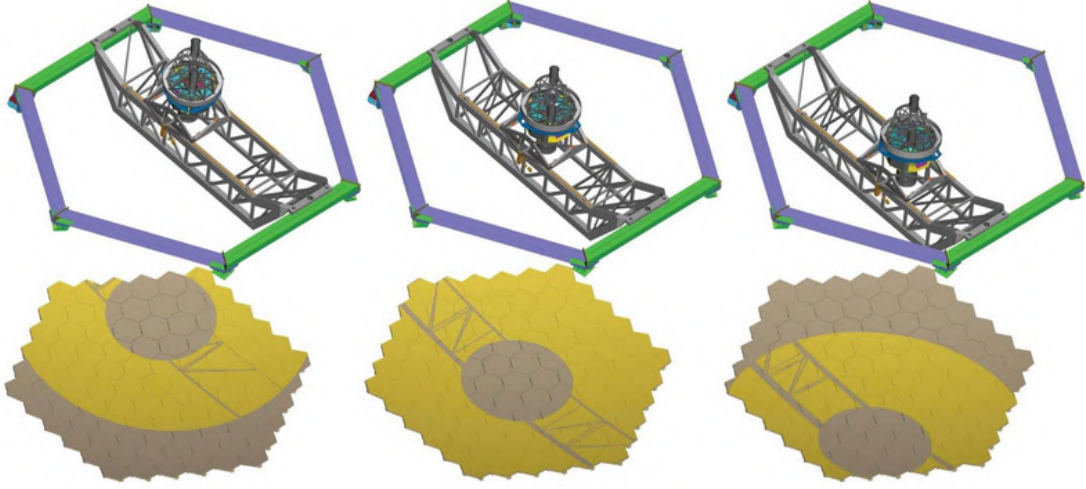


Figure 2.5: The SALT telescope’s moving pupil. Image credit: https://pysalt.salt.ac.za/proposal_calls/current/ProposalCall.html#h.i157iczab4n2

Flux calibration can be applied with the `NOAO.TWODSPEC.LONGSLIT.CALIBRATE()` IRAF command. This command requires the “sensitivity” file for a spectrophotometric standard observed with same configuration as the source being observed. The Python code to create a sensitivity file is listed in section B.

For each of our observations, we took the spectrophotometric standard observed closest to the date of our own observations with the same grating and slit orientation.

11. Heliocentric velocity correction: Due to the Earth’s orbit around the sun, our observations are doppler shifted to a minor degree. This can be corrected with the `NOAO.TWODSPEC.LONGSLIT.DOPCOR()` IRAF command, taking into account the unique time of the observation and the position of SALT.

12. Atmospheric extinction correction: The last correction is for atmospheric extinction. Radiation from the observed source is scattered by the dust and gas within the Earth’s atmosphere.

This can be corrected with the `NOAO.TWODSPEC.LONGSLIT.EXTINCTION()` IRAF command, taking into account the measured airmass during the observation and exposure time of the observation.

Galactic reddening, caused by the dust and gas between the Earth and the galaxies we

observe, could also play a role. However, this is not necessary to correct for during the data reduction process, since FIREFLY automatically corrects for this effect and pPXF is uninfluenced by it when measuring kinematics. See Cappellari (2017) and Wilkinson et al. (2017) for more on pPXF and FIREFLY, respectively.

13. Examine and combine the images together: As previously discussed in section 2.2, multiple observations were taken for J1153 on different dates. The images of these different observations were chosen to be combined to increase the signal-to-noise ratio and quality of the final image. However, the spectral features will not be in the exact same position (same pixel coordinates) on every image. The images can be combined with the `IMAGES.IMMATCH.IMCOMBINE()` IRAF command, but it requires an “offsets” file to overlap and combine the images properly. The coordinates of these spectral features can be found with the `NOAO.IMAGES.TV.IMEXAMINE()` IRAF command. By examining one particular spectral feature on the first taken image and noting the difference in pixel coordinates for the remaining images saved as a matrix in a text file “offsets.list”, we can run `IMCOMBINE()` and combine the images.

14. Aperture extraction: The final step is to extract spectra for the full-spectrum fitting procedures, pPXF and FIREFLY, to measure the spatially-resolved stellar kinematics and stellar populations of our data sample of galaxies.

For the CLoGS BGEs, spectra are extracted with apertures based on the effective radius of each galaxy (as shown in Table 2.1). The following extraction pattern is used to obtain spectra needed to measure the spatially-resolved stellar kinematics of the CLoGS BGEs with pPXF:

- 21 evenly-sized apertures between $-0.25 R_e$ and $+0.25 R_e$ are used to extra spectra for this region.
- Nine evenly-sized apertures between $+0.25 R_e$ and $+0.50 R_e$ are used to extra spectra for this region. Spectra for the region $-0.25 R_e$ and $-0.50 R_e$ are similarly extracted.
- Six evenly-sized apertures between $+0.50 R_e$ and $+0.75 R_e$ are used to extra spectra for this region. Spectra for the region $-0.50 R_e$ and $-0.75 R_e$ are similarly extracted.
- Three evenly-sized apertures between $+0.75 R_e$ and $+1.0 R_e$ are used to extra spectra for this region. Spectra for the region $-0.75 R_e$ and $-1.0 R_e$ are similarly extracted.
- One aperture between $+1.0 R_e$ and $+1.25 R_e$ is used to extra a spectrum for this region. A spectrum for the region $-1.0 R_e$ and $-1.25 R_e$ is similarly extracted.

Further away from the centre of the galaxy, the signal-to-noise of the observation decreases. Therefore, we need bigger apertures when extracting spectra further away from the centre of the galaxy. This extraction pattern is used to obtain an optimal signal-to-noise ratio for the spectra that we extract.

The following extraction pattern is used to obtain spectra needed to measure the spatially-resolved stellar populations of the CLoGS BGEs with FIREFLY:

- An aperture between $0.0 R_e$ and $+0.25 R_e$ is used to extra a spectrum for the inner-right region of the galaxy. Similarly, an aperture between $0.0 R_e$ and $-0.25 R_e$ is used to extra a spectrum for the inner-left region of the galaxy. These two spectra are added together to obtain a single spectrum for the inner region of the galaxy.
- An aperture between $0.25 R_e$ and $+1.0 R_e$ is used to extra a spectrum for the inner-right region of the galaxy. Similarly, an aperture between $-0.25 R_e$ and $-1.0 R_e$ is used to extra a spectrum for the inner-left region of the galaxy. These two spectra are combined to obtain a single spectrum for the outer region of the galaxy.

Similar extraction patterns are used for the MHONGOOSE galaxy J1153 to measure its stellar kinematics; except, in stead of using an effective radius R_e for J1153, we use 4 kpc for the galaxy’s major axis and 1 kpc for the galaxy’s minor axis. For measuring the stellar populations of J1153, unique spectra will be extracted. This will be elaborated upon in section 3.4. The Python code used to extract spectra for the CLoGS BGEs and J1153 is listed in B.

Finishing up: By following these aforementioned steps, final spectroscopic images for each galaxy, such as in Figure 2.6, were obtained for our data sample of galaxies.

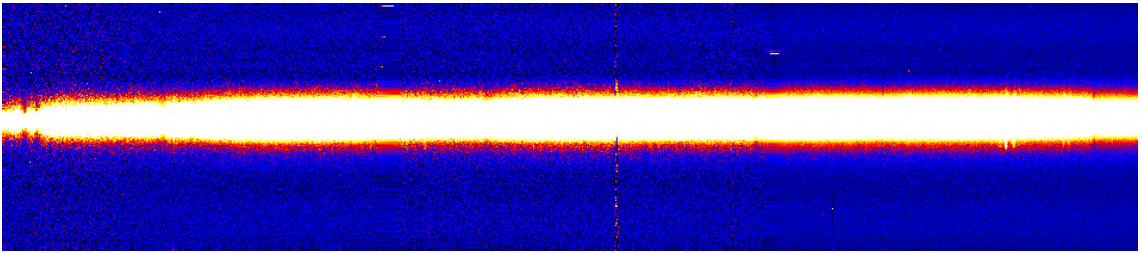


Figure 2.6: Final spectroscopic image of ESO 507-25. The cosmic rays, telluric lines and unnecessary background data is cleaned from this image.

These images were then used to extract the necessary spectra needed, such as Figure 2.7, to measure the spatially-resolved stellar kinematics and stellar populations of these galaxies with pPXF and FIREFLY.

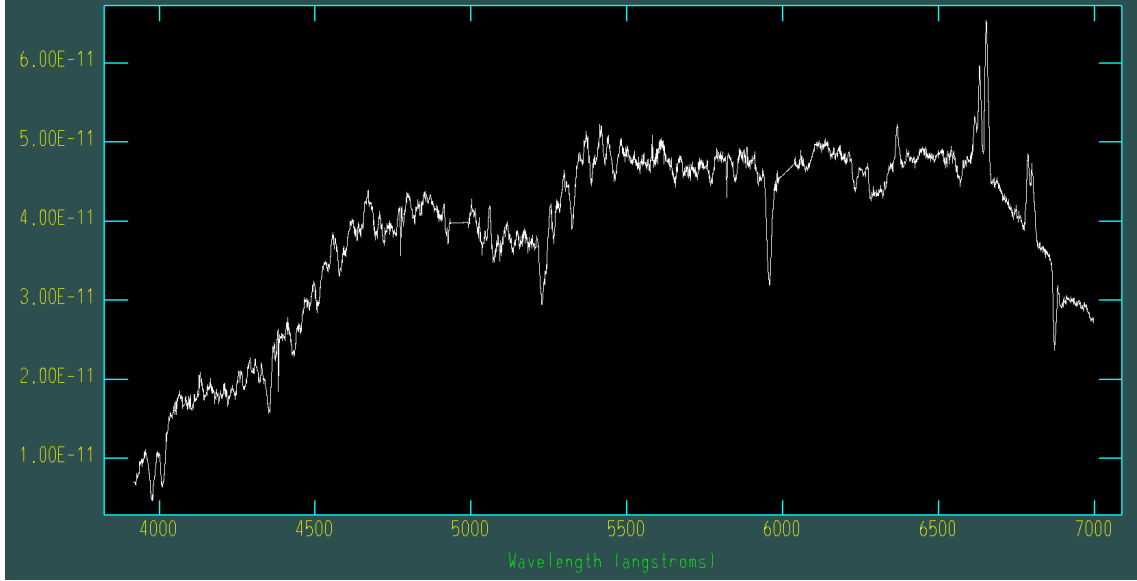


Figure 2.7: Spectrum of ESO 507-25’s inner region as extracted from its final spectroscopic image. The spectrum shows a clear stellar continuum with absorption features as well as gas emission features.

2.5 Full-spectrum Fitting with Penalised PiXel Fitting (pPXF)

To measure the spatially-resolved stellar kinematics of our data sample of galaxies, we use the full-spectrum fitting software pPXF by Cappellari (2017).

2.5.1 pPXF and its Working Principles

Penalised Pixel Fitting (pPXF) is a package of full-spectrum fitting software developed by Cappellari and Emsellem (2004) and later improved upon by Cappellari (2017). This software can be implemented in Python and is publicly available at: <https://www-astro.physics.ox.ac.uk/~mxc/software/#ppxf>.

pPXF is developed to measure the stellar kinematics and gas kinematics of galaxies by fitting their full spectra (Cappellari and Emsellem, 2004). The pPXF algorithm starts by asking the user for an initial guess for the Line-of-Sight-Velocity-Distribution (LOSVD) parameters, such as the rotational velocity V and velocity dispersion σ while keeping the Gauss-Hermite (h3, h4...) parameters constant (Cappellari and Emsellem, 2004). pPXF then determines the best fitting LOSVD parameters by modelling the galaxy spectrum with the following equation (Cappellari and Emsellem, 2004):

$$G_{mod}(x) = \sum_{k=1}^K w_k [B * T_k](x) + \sum_{l=0}^L b_l \mathcal{P}_l(x) \quad w_k \geq 0 \quad (2.3)$$

where w_k and b_l are the weights to be fitted, $B(x) = \mathcal{L}(cx)$ is the spectral broadening function of the LOSVD $\mathcal{L}$, with c the speed of light. $*$ indicates convolution and T_k is the library of k stellar templates. $\mathcal{P}_l$ are the set of Legendre polynomials of order l that adjust the stellar templates to best fit the spectrum (Cappellari and Emsellem, 2004).

The weights w_k and b_l are calculated by minimising the χ^2 function, given as (Cappellari and Emsellem, 2004):

$$\chi^2 = \sum_{n=1}^N r_n^2 \quad (2.4)$$

where r_n are the residuals defined as (Cappellari and Emsellem, 2004):

$$r_n = \frac{G_{mod}(x_n) - G(x_n)}{\Delta G(x_n)} \quad (2.5)$$

with $G(x_n)$ the observed galaxy spectrum.

The idea of “penalised pixel fitting” by Cappellari and Emsellem (2004) is to fit the LOSVD parameters (V , σ , h_3 , ..., h_M) simultaneously while adding a penalty term to the calculated χ^2 value (Cappellari and Emsellem, 2004). This penalty term biases the solution to fit the line profiles on the spectrum as a Gaussian shape, χ^2 then becomes penalised as (Cappellari and Emsellem, 2004):

$$\chi_p^2 = \chi^2 + \alpha \mathcal{P} \quad (2.6)$$

where α is some constant and $\mathcal{P}$ is the penalisation function.

Cappellari and Emsellem (2004) define this penalisation function as:

$$\mathcal{P} = \mathcal{D}^2 = \frac{\int_{-\infty}^{\infty} [\mathcal{L}(v) - \mathcal{G}(v)]^2 dv}{\int_{-\infty}^{\infty} \mathcal{G}(v)^2 dv} \approx \sum_{m=3}^M h_m^2 \quad (2.7)$$

where $\mathcal{L}(v)$ is the line profile of the spectral feature, $\mathcal{G}(v)$ is its best-fitting Gaussian and h_m are the Gauss-Hermite parameters.

pPXF iteratively adjusts the residuals by linear perturbation and refits the spectrum

to optimally measure the kinematics from the spectrum. The residuals are adjusted as (Cappellari and Emsellem, 2004):

$$r'_n = r_n + \lambda \sigma(\mathbf{r}) \mathcal{D} \quad (2.8)$$

where $\sigma^2(\mathbf{r})$ is the statistical variance of the residuals:

$$\sigma^2(\mathbf{r}) = \frac{1}{N} \sum_{n=1}^N r_n^2 \quad (2.9)$$

Essentially, the χ^2 function becomes iteratively penalised as:

$$\chi_P^2 = \chi^2(1 + \lambda^2 \mathcal{D}^2) \quad (2.10)$$

which is the target function to be minimised during each fit.

Improvements that were made to pPXF by Cappellari (2017) include a better use of stellar templates, which can be read about in section 2.1 of Cappellari (2017). The latest version of pPXF to date takes into account the instrumental Gaussian dispersion σ_{inst} and template Gaussian dispersion σ_{temp} of the observation to more accurately fit the velocity dispersion from the spectrum. This is essential for cases where there is a large difference between σ_{inst} and σ_{temp} .

2.5.2 Using pPXF to Measure Stellar Kinematics

As previously stated, we are primarily interested in using pPXF to measure the stellar kinematics of our sample of galaxies. pPXF allows us to measure the LOSVD parameters of each galaxy using their spectra, such as their stellar rotational velocity V and stellar velocity dispersion σ . Since spectra were obtained for several different regions of each galaxy, as discussed in section 2.4, we can measure the spatially-resolved stellar kinematics of each galaxy with pPXF. This is achieved by measuring the LOSVD parameters for each aperture. For our purposes, we mostly use the default parameters for pPXF. We also use the default stellar library for pPXF: MILES, which is previously discussed in section 1.4.3. The pPXF parameters for which we do not use the default values are:

- degree: We prefer multiplicative Legendre Polynomials over additive Legendre Polynomials when using pPXF, and therefore we deactivate this parameter by setting `degree = -1`. Multiplicative Legendre Polynomials are more computationally intensive, but arguably more accurate.

- `mdegree`: Since we prefer the use of multiplicative Legendre Polynomials, we must specify the order of these polynomials. We use `mdegree = 10`, which through experimentation provided the best quality of fits.
- `regul`: We use the suggestion of the pPXF manual to normalise the stellar templates and galaxy spectrum by their median and to apply a regulation error of 0.01, i.e: $\text{regul} = 1 / \text{regul_err}$, where `regul_err = 0.01`.
- `bias`: In our case, we use a Monte-Carlo simulation of 50 iterations of pPXF to estimate the values and errors of the stellar kinematics. According to the pPXF manual, when following this procedure, the bias parameter can be set to zero.

The purpose of running pPXF iteratively as a Monte-Carlo simulation is to more accurately constrain the measurement errors. pPXF is particularly sensitive to the amount of noise in the galaxy spectrum and therefore a single run of pPXF does not necessarily provide trustworthy results. After running pPXF once for a given galaxy spectrum and obtaining a good fit, we perform our Monte-Carlo simulation. We add a random degree of noise to each pixel on the galaxy spectrum within one standard deviation of its signal and refit the spectrum with pPXF. This is done for 50 iterations. We take the average value measured for the stellar kinematics by the Monte-Carlo simulation as our final result and we take the standard deviation of these values as the error. This needs to be done for all the spectra extracted with different apertures for each galaxy. This provides us with the spatially-resolved stellar kinematics for our data sample of galaxies.

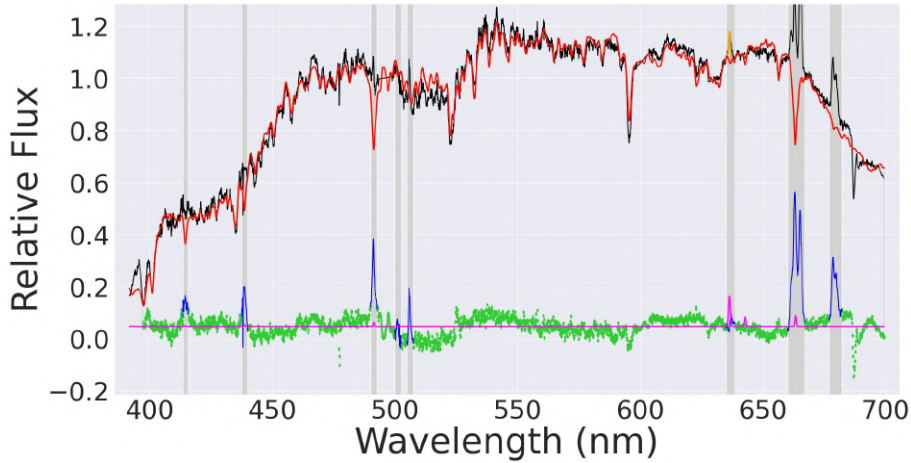


Figure 2.8: Example first iteration pPXF fit of ESO 507-25’s central spectrum. The observed spectrum of ESO 507-25 is shown in black. pPXF’s best fitting solution is shown in red. The chipgaps and gas emission lines (shown in orange and blue) are masked in grey. The baseline fit is shown in pink. The deviations between the data and the model spectra are shown in green.

With our Monte-Carlo pPXF simulations, we measure the stellar kinematics V and σ

of each galaxy spectrum extracted at every region. This provides us with the spatially-resolved stellar kinematics of our data sample of galaxies.

All fitted spectra for this thesis are available for viewing at https://drive.google.com/drive/folders/1Zx_btut-Y5IQ6_R9Im9g_jc39W0qVGii.

The complete set of pPXF results is further shown in sections 3.1 and 3.3 for the CLoGS BGEs and J1153, respectively.

2.6 Full-spectrum Fitting with FIREFLY

To measure the spatially-resolved stellar populations of our data sample of galaxies, we use the full-spectrum fitting software FIREFLY by Wilkinson et al. (2017).

2.6.1 FIREFLY and its working principles

“Fitting iteratively for likelihood analysis”, or FIREFLY by Wilkinson et al. (2017), is a package of full-spectrum fitting developed for deriving the stellar populations and star-formation properties of galaxies from their spectra. This software is written in Python and is publicly available at: https://github.com/FireflySpectra/firefly_release.

FIREFLY uses a χ^2 minimisation technique to fit spectra, using several well-known stellar libraries such as MILES, STELIB, ELODIE and the like (Wilkinson et al., 2017). Unlike pPXF, FIREFLY does not apply any additive or multiplicative polynomials to adjust the stellar templates when fitting the spectrum (Wilkinson et al., 2017). Instead, FIREFLY is specifically programmed to fit galaxy spectra and takes into effect the unique properties that could affect a galaxy’s spectrum, such as its intrinsic spectral energy distribution (SED) degeneracies and its galactic extinction (Wilkinson et al., 2017). FIREFLY is a proven method for determining the stellar age, metallicity, stellar mass and the star-formation properties of galaxies above a signal-to-noise ratio of $S/N \sim 5$ (Wilkinson et al., 2017).

FIREFLY works on the basis of fitting several model single stellar populations (SSPs) to a galaxy spectrum and determines which linear combination of SSPs best fits the spectrum (Wilkinson et al., 2017). For instance, the spectrum of the galaxy $L(\lambda)$ is approximated as:

$$L(\lambda) = \sum_i^{n_{SSP}} a_i L_{SSP_i}(\lambda) \quad (2.11)$$

where $L(\lambda)$ is the luminosity of the galaxy at wavelength λ , a_i are the weights to be determined and $L_{SSP}(\lambda)$ are the luminosities of the SSPs at wavelength λ and n_{SSP} are the number of SSPs.

For each model SSP, FIREFLY calculates its χ^2 value as (Wilkinson et al., 2017):

$$\chi^2 = \sum_{\lambda} \frac{(F_{\text{data}}(\lambda) - F_{\text{model}_i}(\lambda))^2}{\sigma(\lambda)^2} \quad (2.12)$$

where $F_{\text{data}}(\lambda)$ is the flux of the data at wavelength λ , $F_{\text{data}}(\lambda)$ is the flux of the model at wavelength λ and σ is the error at wavelength λ . FIREFLY typically recovers ~ 1000 possible combinations of SSPs that fit the galaxy's spectrum (Wilkinson et al., 2017). To determine the most statistically likely combination of SSPs, the calculated χ^2 values of the SSPs need to be weighted by their corresponding probabilities (Wilkinson et al., 2017). The χ^2 probability distribution function is well-known as:

$$P(X = \chi_0^2) = \int_{\chi_0^2}^{\infty} \frac{1}{2^{(k/2)}\Gamma(\frac{k}{2})} X^{(k/2)-1} e^{-X/2} dX \quad (2.13)$$

where $\Gamma(z) = \int_0^{\infty} x^{z-1} e^{-x} dx$ is the well-known Gamma function, χ_0^2 is the chi-squared value, k is the number of degrees of freedom defined as: $k = N - \nu - 1$. In this case, N (the number of observations) is the number of data points on the spectrum and ν is the number of fitting parameters FIREFLY uses.

The flux of the best fitting solution is therefore (Wilkinson et al., 2017):

$$F(\lambda) = \sum_i^{\text{fits}} \frac{P(\chi^2(i)) F_i(\lambda)}{\sum P(\chi^2(i))} \quad (2.14)$$

2.6.2 Using FIREFLY to Measure Stellar Populations

For our purposes, we wish to determine the stellar population properties of the inner and outer regions of our data sample of galaxies. As part of the data reduction process, spectra were specifically extracted with apertures spanning across these regions for every galaxy, as discussed in section 2.4.

We fit these spectra with every possible stellar library in FIREFLY, namely MILES, STELIB, ELODIE, MARCS, Th-MaStar and E-MaStar, as discussed in section 1.4.3. FIREFLY can fit model stellar populations, assuming either a Kroupa IMF or Salpeter IMF, as discussed in section 1.3.3. With FIREFLY, each stellar library can be used in

combination with any IMF (Kroupa or Salpeter), excluding the MARCS stellar library. An example FIREFLY fit is shown in Figure 2.9.

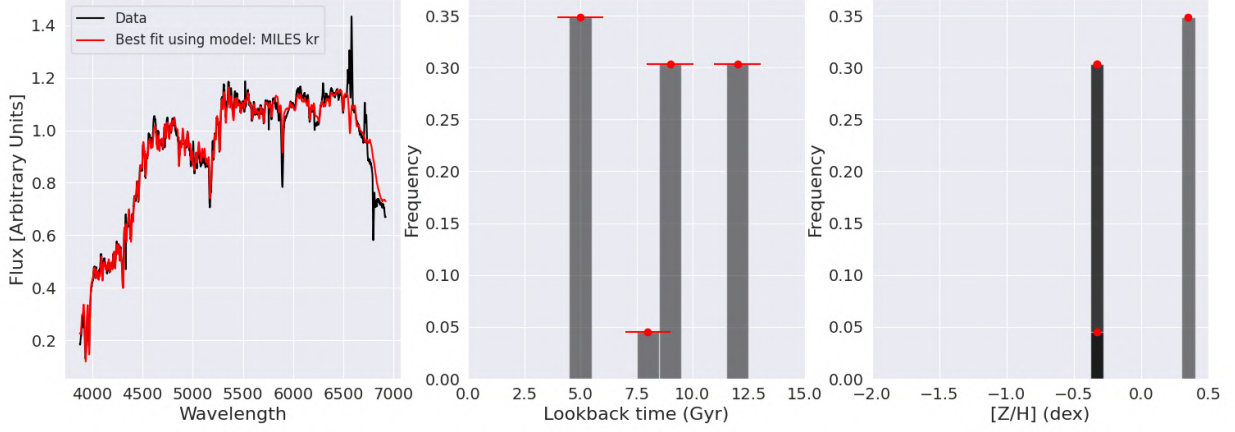


Figure 2.9: Example FIREFLY fit: Stellar populations of ESO 507-25's inner region derived with FIREFLY. In this case, the MILES stellar library was used assuming a kroupa IMF.

All fitted spectra for this thesis are available for viewing at https://drive.google.com/drive/folders/1Zx_btut-Y5IQ6_R9Im9g_jc39W0qVGii.

The complete set of FIREFLY results is further shown in sections 3.2 and 3.4 for the CLoGS BGEs and J1153, respectively.

Chapter 3

Results

“One, remember to look up at the stars and not down at your feet. Two, never give up work. Work gives you meaning and purpose and life is empty without it. Three, if you are lucky enough to find love, remember it is there and do not throw it away.”

Stephen Hawking

As discussed in sections 1.5.1 and 1.5.2, our research aims are to measure the spatially-resolved stellar kinematics and stellar populations of the CLoGS BGEs and the MHONGOOSE galaxy J1153. The spatially-resolved stellar kinematics are measured with the full-spectrum fitting software pPXF, as discussed in section 2.5. The stellar populations are measured with the full-spectrum fitting software FIREFLY, as discussed in section 2.6. In this chapter the spatially-resolved stellar kinematics and stellar populations for the CLoGS BGEs as well as the MHONGOOSE galaxy J1153 are presented.

3.1 Spatially-resolved Stellar Kinematics of the CLoGS BGEs

As previously discussed in section 2.5, we measure the LOSVD parameters of each galaxy with pPXF. Of interest are the rotational velocity, V , and velocity dispersion, σ , of each galaxy, and how these properties change with radius. For this reason, we generate stellar velocity dispersion profiles and stellar rotational velocity profiles for each galaxy.

The stellar velocity dispersion profiles show the relationship between the velocity dispersion of the stars in the galaxy, σ , at a certain radius R . The velocity dispersion is normalised by the central velocity dispersion, σ_0 , which is measured from 0 – 1 kpc (centered at 0.5 kpc on velocity dispersion profile). Similarly, the radius is normalised by

$R_0 = 1$ kpc.

To determine the slope of these velocity dispersion profiles, we stack the left-hand side and right-hand side pPXF results together and fit a function through the velocity dispersion measurements. This can be done, since the velocity dispersion is expected to be symmetric about the galactic centre for these early-type galaxies. We use the following function to fit the data:

$$\log\left(\frac{\sigma_R}{\sigma_0}\right) = \eta \cdot \log\left(\frac{R}{R_0}\right) + c \quad c \in \mathbb{R} \quad (3.1)$$

where η is the slope of the velocity dispersion profile. This is equivalent to fitting the following power law function, similar to that of Loubser et al. (2018):

$$\frac{\sigma_R}{\sigma_0} = C\left(\frac{R}{R_0}\right)^\eta \quad C \in \mathbb{R} \quad (3.2)$$

Other functions such as a broken power law can be used for determining the shape of the profile; however, these functions are not physically motivated (Veale et al., 2017). Throughout this section, we will show the velocity dispersion profiles of the CLoGS BGEs and their best fitting parameters ($\eta \pm \Delta\eta$, $c \pm \Delta c$). Further in this section, we will show the stellar rotational velocity profiles of the CLoGS BGEs. The finding charts of the CLoGS BGEs can be found in Appendix A to understand what these profiles visually represent.

To determine the degree of rotation of the stars within these galaxies, we identify V_{upper} and V_{lower} by eye, where the rotational velocity converges. A strongly rotating galaxy would have a characteristic ‘S’- or ‘Z’- shaped (anti-symmetric) profile, with a large difference between V_{upper} and V_{lower} . The maximum degree of rotation of the galaxy V_{max} would be the difference in velocity about the centre of the galaxy (at $R = 0$). More specifically, V_{max} is defined as $V_{max} = (V_{upper} - V_{lower})/2$. Galaxies with no clear difference between V_{upper} and V_{lower} can be classified as non-rotating.

The stellar kinematics of the CLoGS BGEs, such as their velocity dispersion slopes η and their anisotropy parameters V_{max}/σ_0 , summarised in Table 3.1, can be compared with that of other galaxy surveys and galaxy evolution simulations. This will be done in Chapter 4. Such comparative studies are important to ultimately constrain the dark matter content of these galaxies, as further discussed in Chapter 4.

In this section we show the spatially-resolved stellar kinematics of NGC 128, NGC 193 and NGC 5084. The results for the remaining CLoGS BGEs are presented in Appendix D. A summary of all results is provided by Table 3.1.

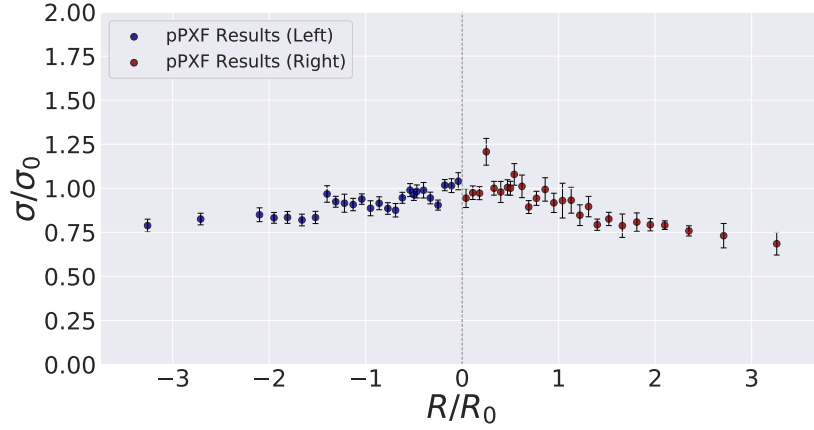


Figure 3.1: Stellar velocity dispersion profile of NGC 128. The profile is approximately symmetric about the galactic centre and decreases slightly towards both sides.

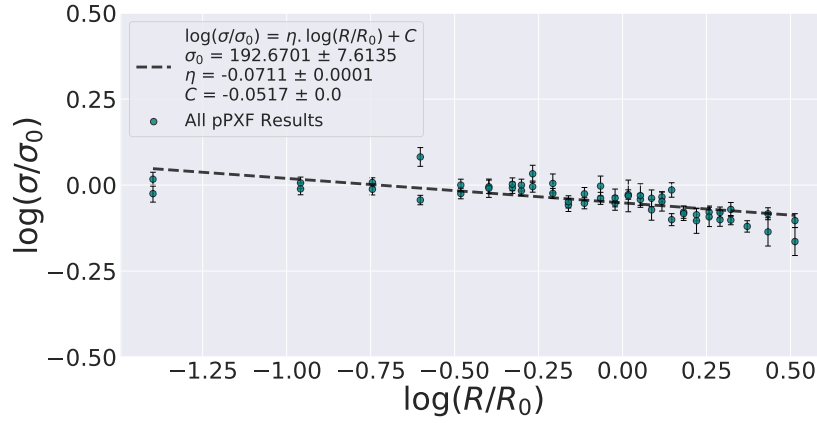


Figure 3.2: Stellar velocity dispersion slope of NGC 128. The slope is small and negative. The profile can be interpreted as slightly decreasing.

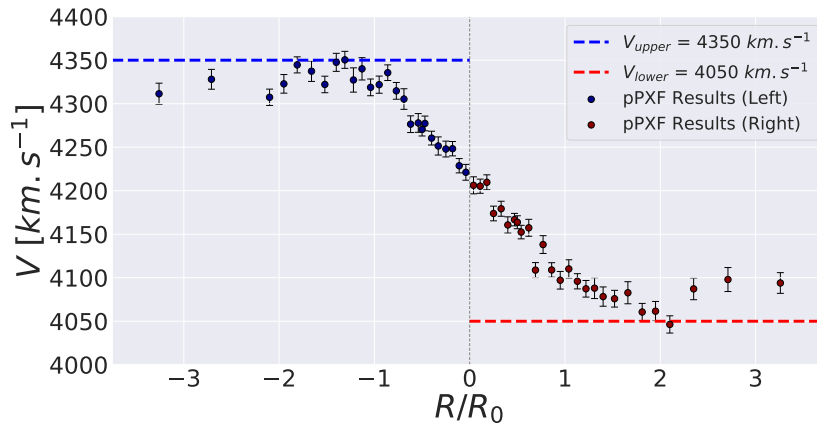


Figure 3.3: Rotational velocity profile of NGC 128. The pPXF results show that NGC 128 has strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 150 \text{ km.s}^{-1}$.

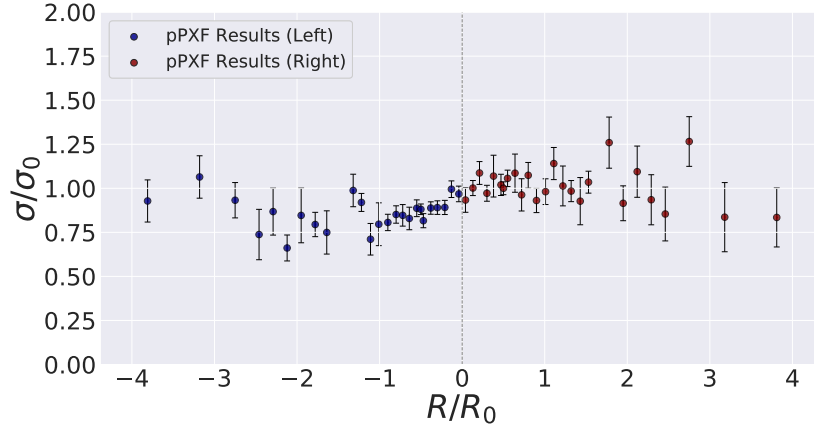


Figure 3.4: Stellar velocity dispersion profile of NGC 193. The profile is approximately symmetric about the galactic centre and flat overall.

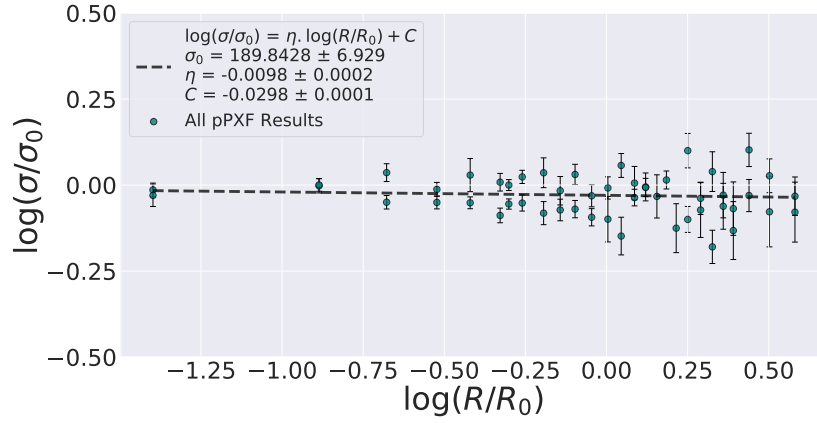


Figure 3.5: Stellar velocity dispersion slope of NGC 193. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

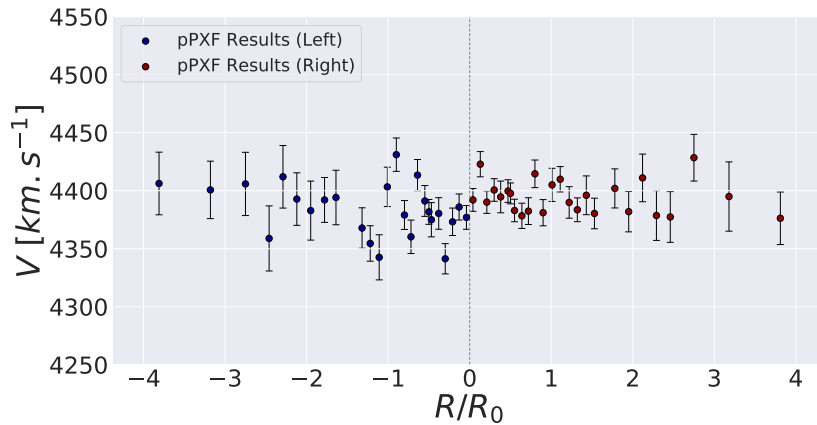


Figure 3.6: Rotational velocity profile of NGC 193. The pPXF results show that NGC 193 has no clearly discernible rotation.

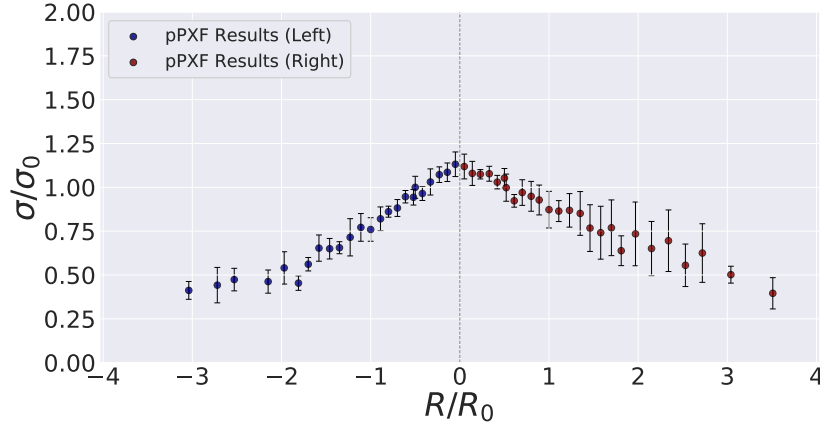


Figure 3.7: Stellar velocity dispersion profile of NGC 5084. The profile is approximately symmetric about the galactic centre and decreases to both sides.

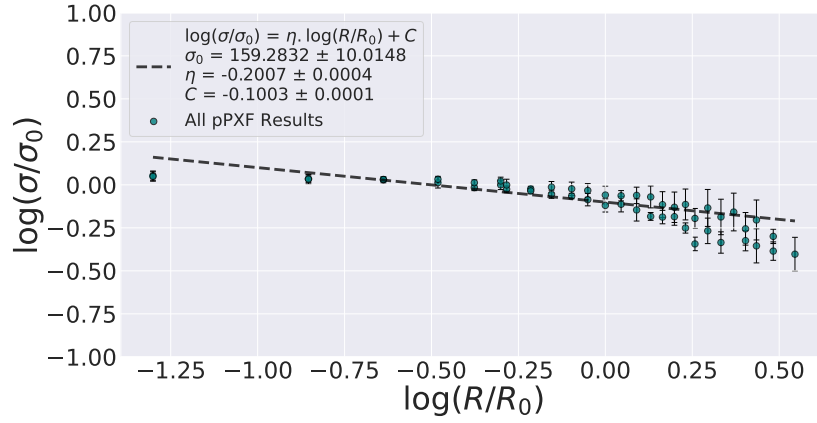


Figure 3.8: Stellar velocity dispersion slope of NGC 5084. The slope is negative. The profile can be interpreted as decreasing.

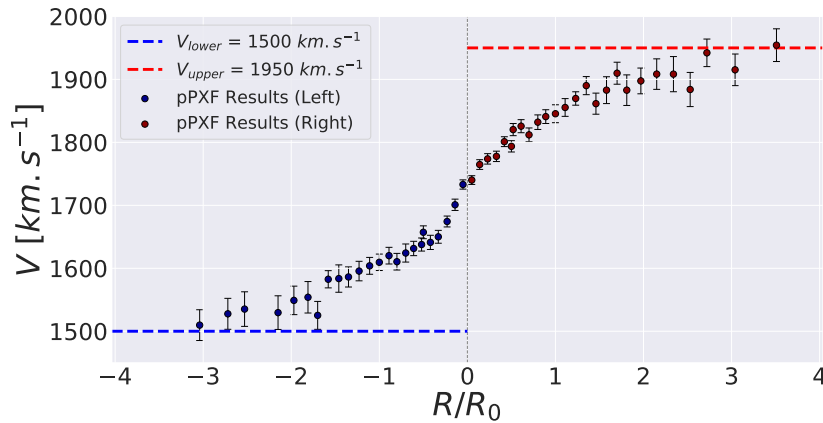


Figure 3.9: Rotational velocity profile of NGC 5084. The pPXF results show that NGC 5084 has very strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 225 \text{ km.s}^{-1}$.

Table 3.1: Stellar kinematics of the CLoGS BGEs. For each CLoGS BGE, we show their maximum degree of rotation, V_{max} , central velocity dispersion σ_0 , anisotropy parameter, V_{max}/σ_0 , and velocity dispersion slope, η . Galaxies with no clear stellar rotation have no V_{max} measurement.

Name	V_{max}	σ_0	V_{max}/σ_0	η
ESO507	50.0 ± 11.69	200.04 ± 9.27	0.25 ± 0.28	-0.0091 ± 0.0001
NGC128	150.0 ± 9.93	192.67 ± 7.61	0.78 ± 0.11	-0.0711 ± 0.0001
NGC1395	100.0 ± 10.4	193.87 ± 7.53	0.52 ± 0.14	-0.0043 ± 0.0
NGC1550	-	220.49 ± 7.19	-	0.0099 ± 0.0005
NGC193	-	189.84 ± 6.93	-	-0.0098 ± 0.0002
NGC2292	-	141.89 ± 11.3	-	0.0261 ± 0.0004
NGC2911	-	163.14 ± 6.9	-	0.0637 ± 0.0005
NGC3078	125.0 ± 10.17	200.11 ± 5.15	0.62 ± 0.11	-0.0047 ± 0.0
NGC3325	-	127.39 ± 13.03	-	0.0395 ± 0.0003
NGC3923	-	206.56 ± 7.92	-	-0.0007 ± 0.0001
NGC4697	112.5 ± 17.49	153.68 ± 6.97	0.73 ± 0.2	-0.0084 ± 0.0001
NGC5044	-	190.29 ± 7.81	-	-0.0006 ± 0.0
NGC5061	-	157.13 ± 5.91	-	0.0127 ± 0.0001
NGC5084	225.0 ± 15.86	159.28 ± 10.01	1.41 ± 0.13	-0.2007 ± 0.0004
NGC5153	125.0 ± 29.56	118.4 ± 10.55	1.06 ± 0.33	0.0197 ± 0.0006
NGC5903	-	147.21 ± 5.49	-	0.0209 ± 0.0001
NGC7252	-	142.97 ± 23.11	-	0.0466 ± 0.0005
NGC7377	-	125.79 ± 5.61	-	0.0594 ± 0.0005

From Table 3.1 it is clear that 7 out of the 18 CLoGS BGEs show a marginal amount of rotation. The strongest rotating galaxies include NGC 128, NGC 4697, NGC 5084 and NGC 5153, all of which have an anisotropy parameter $V_{max}/\sigma_0 \gtrsim 0.75$.

A wide variety of stellar velocity dispersion slopes are measured. However, most of the velocity dispersion slopes fall in the range $-0.1 \leq \eta \leq 0.1$, save that of NGC 5084 with a slope of $\eta \approx -0.2$.

These results are discussed in more detail in Chapter 4, in which the stellar kinematics of the CLoGS BGEs are compared with other galaxy surveys and galaxy evolution simulations. These comparisons will reveal how the stellar kinematics of the CLoGS BGEs are unique among other types of galaxies.

3.2 Stellar Populations of the CLoGS BGEs

Of further interest are the stellar populations of the CLoGS BGEs measured with FIREFLY, as discussed in section 2.6. FIREFLY will measure the components of each galaxy’s stellar population from their spectra and provide their estimate ages, metallicities, luminosity fractions and mass fractions. We use FIREFLY to measure the stellar populations of each CLoGS BGE’s inner ($0.0 - 0.25 R_e$) and outer region ($0.25 - 1.0 R_e$), as discussed in section 2. When measuring stellar populations, FIREFLY takes into account the effect of dust attenuation. Similar to Wilkinson et al. (2015), we assume the dust attenuation law of Calzetti et al. (1994) when using FIREFLY. We are primarily interested in whether young stellar populations could be found within either the inner or outer regions of the CLoGS BGEs.

As previously discussed in section 2.6, we use every possible stellar library in FIREFLY to measure the stellar populations of the inner and outer regions of the CLoGS BGEs. These stellar libraries include MILES, STELIB, ELODIE, MARCS and MaStar, as discussed in section 1.4.3. The Salpeter IMF provides stellar masses for early-type galaxies in agreement with several gravitational lensing studies, such as Treu et al. (2010) and Sonnenfeld et al. (2015). Therefore, we assume a Salpeter IMF when using FIREFLY.

Due to the different ingredients of each stellar library, the measured stellar populations will differ. We take into account the reduced chi-squared, χ_ν^2 , value of each FIREFLY fit to obtain a systemic error for it. Each IMF and stellar library combination uses a finite number of SSP models (see Table 1 of Wilkinson et al., 2017). Furthermore, the age and metallicity of each SSP are measured over a grid of values, depending on the model used. Therefore, only a certain set of discrete ages and metallicities will be measured, as shown by the example FIREFLY fit in Figure 2.9.

To demonstrate, we show the ages, metallicities, luminosity fractions and mass fractions of each stellar population component of ESO 507-25’s inner and outer region, as shown in Table 3.2. The same properties are measured for all of the CLoGS BGEs. The complete set of FIREFLY results for our sub-sample of CLoGS BGEs is listed in Appendix E in tabular format.

We further calculate a χ_ν^2 -weighted age for each CLoGS BGE’s inner and outer region, based on the light-weighted ages measured by each stellar library and their corresponding χ_ν^2 statistic. These ages are listed in Table 3.3. For our purposes, we only consider the MILES, STELIB and ELODIE stellar libraries when calculating the χ_ν^2 -weighted ages, since these libraries provide the highest quality of fit with χ_ν^2 closer to 1.

The χ_ν^2 -weighted ages are calculated with equation 3.3 using weights w_i , where $i = 1$ denotes MILES, $i = 2$ denotes STELIB and $i = 3$ denotes ELODIE. We use the goodness-of-fit (χ_ν^2 statistics) to inversely weigh the ages such that the best fits, with χ_ν^2 close to 1 are weighed heavier when calculating the average age.

$$\chi_\nu^2\text{-weighted age} = \sum_i^3 w_i \cdot \text{age}_i, \quad 1 \leq i \leq 3, i \in \mathbb{N} \quad (3.3)$$

The weights are calculated with equations 3.4 and 3.5, where $\chi_{\nu,1}^2$ is the χ_ν^2 statistic of MILES, $\chi_{\nu,2}^2$ is the χ_ν^2 statistic of STELIB and $\chi_{\nu,3}^2$ is the χ_ν^2 statistic of ELODIE.

$$w_i = \frac{\delta_i}{\sum_j^3 \delta_j}, \quad 1 \leq j \leq 3, j \in \mathbb{N} \quad (3.4)$$

$$\delta_j = \frac{1}{|1 - \chi_{\nu,j}^2|} \quad (3.5)$$

The χ_ν^2 -weighted ages are useful, since it provides singular, statistically significant values for the inner and outer stellar populations of the CLoGS BGEs. This allows us to easily discuss the average ages of the stellar populations and to more conveniently relate our results with other available information. For instance, these results will later be compared with the known multi-wavelength properties of the CLoGS BGEs in section 4. This will include information such as the X-ray and radio morphologies of the CLoGS BGE's hosting groups, e.g. Kolokythas et al. (2018). The stellar population ages of the CLoGS BGEs will also be compared with their cold gas content, e.g. O'Sullivan et al. (2018a) and Kolokythas et al. (2022). This is further discussed in section 4.

Table 3.2: Luminosity weighted stellar populations of ESO 507-25’s inner and outer region measured with FIREFLY, assuming a Salpeter IMF. The χ^2_ν statistic of each FIREFLY fit is shown. The results for the remaining CLoGS BGEs are listed in Appendix E.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.912	1	$9.0^{+1.04}_{-1.11}$	$-0.33^{+0.07}_{-0.02}$	74.26	75.69
			2	$5.0^{+1.01}_{-1.04}$	$0.35^{+0.02}_{-0.01}$	24.75	22.39
			3	$11.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	1.92
	Outer	0.207	1	$12.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	98.93
			2	$0.9^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	1.07
STELIB	Inner	1.082	1	$7.0^{+1.02}_{-1.02}$	$-0.33^{+0.01}_{-0.02}$	31.25	18.83
			2	$12.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.02}$	31.25	50.58
			3	$8.0^{+1.01}_{-1.02}$	$-0.33^{+0.01}_{-0.02}$	25.0	16.91
			4	$11.0^{+1.01}_{-1.01}$	$0.0^{+0.0}_{-0.01}$	12.5	13.69
	Outer	0.262	1	$4.0^{+1.01}_{-1.09}$	$0.0^{+0.04}_{-0.03}$	66.01	58.71
			2	$7.0^{+1.0}_{-1.04}$	$-0.33^{+0.02}_{-0.02}$	33.0	41.2
			3	$0.2^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.09
	Inner	0.945	1	$10.0^{+1.14}_{-1.04}$	$-0.33^{+0.0}_{-0.0}$	50.0	79.05
			2	$1.5^{+1.14}_{-1.04}$	$0.35^{+0.0}_{-0.0}$	50.0	20.95
ELODIE	Outer	0.249	1	$11.0^{+1.07}_{-1.0}$	$-0.33^{+0.0}_{-0.04}$	90.91	99.08
			2	$0.6^{+1.01}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.92
	Inner	0.002	1	$1.0^{+1.08}_{-1.24}$	$0.2^{+0.0}_{-0.04}$	90.91	90.22
			2	$1.0^{+1.01}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	9.09	9.78
	Outer	0.002	1	$1.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	90.91	99.65
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.35
E-MaStar	Inner	0.002	1	$1.0^{+1.08}_{-1.24}$	$0.2^{+0.0}_{-0.04}$	90.91	90.22
			2	$1.0^{+1.01}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	9.09	9.78
	Outer	0.002	1	$1.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	90.91	99.65
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.35
	Inner	0.002	1	$1.0^{+1.08}_{-1.24}$	$0.2^{+0.0}_{-0.04}$	90.91	90.22
			2	$1.0^{+1.01}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	9.09	9.78
Th-MaStar	Outer	0.002	1	$1.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	90.91	99.65
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.35
	Inner	0.002	1	$1.0^{+1.08}_{-1.24}$	$0.2^{+0.0}_{-0.04}$	90.91	90.22
			2	$1.0^{+1.01}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	9.09	9.78

Table 3.3: Luminosity-weighted- and χ^2_ν -weighted stellar population ages of the CLoGS BGEs. The χ^2_ν -weighted ages are measured from the MILES-, STELIB- and ELODIE luminosity-weighted ages and their χ^2_ν statistics. The χ^2_ν values are listed in Table 3.2 and throughout Tables E.1 - Table E.19. We include the ages of NGC 2293, the close neighbour of the BGE NGC 2292, as well as NGC 5152, the close neighbour of the BGE NGC 5153.

Galaxy	Region	MILES	STELIB	ELODIE	χ^2_ν -weighted age
		Luminosity-weighted age	Luminosity-weighted age	Luminosity-weighted age	
ESO 507	Inner	7.8 ± 2.87	9.06 ± 0.87	3.87 ± 2.12	6.5 ± 2.0
	Outer	9.48 ± 5.41	4.67 ± 1.17	8.44 ± 4.97	7.5 ± 3.8
NGC 128	Inner	5.6 ± 3.66	3.92 ± 0.97	2.12 ± 1.09	4.0 ± 1.5
	Outer	5.25 ± 1.64	3.88 ± 0.98	4.31 ± 1.41	4.5 ± 1.3
NGC 193	Inner	11.49 ± 2.47	9.39 ± 4.32	7.47 ± 3.96	9.3 ± 3.7
	Outer	7.4 ± 1.31	8.44 ± 1.69	10.97 ± 2.54	8.9 ± 1.8
NGC 1395	Inner	7.21 ± 2.25	5.93 ± 3.4	8.58 ± 1.94	7.3 ± 2.5
	Outer	8.85 ± 4.95	4.17 ± 2.09	3.35 ± 1.26	5.3 ± 2.7
NGC 1550	Inner	9.73 ± 1.62	9.09 ± 1.6	7.9 ± 1.36	9.2 ± 1.6
	Outer	11.48 ± 0.19	11.9 ± 1.75	12.36 ± 2.86	12.2 ± 2.4
NGC 2292	Inner	8.36 ± 3.05	4.57 ± 1.46	3.43 ± 0.77	3.7 ± 0.9
	Outer	8.85 ± 2.1	2.01 ± 2.52	8.53 ± 2.71	6.5 ± 2.4
NGC 2293	Inner	11.17 ± 3.75	7.51 ± 3.45	8.01 ± 2.31	8.7 ± 3.5
	Outer	8.06 ± 1.16	6.65 ± 1.66	5.47 ± 1.29	6.7 ± 1.4
NGC 2911	Inner	8.91 ± 4.44	5.53 ± 1.83	5.86 ± 4.63	7.2 ± 3.3
	Outer	5.42 ± 1.68	3.43 ± 0.77	5.96 ± 2.19	5.0 ± 1.6
NGC 3078	Inner	7.17 ± 2.12	12.19 ± 2.62	6.39 ± 2.57	10.5 ± 2.5
	Outer	5.68 ± 2.62	12.57 ± 5.5	10.24 ± 3.95	9.5 ± 4.0
NGC 3325	Inner	10.82 ± 1.41	2.38 ± 0.48	9.28 ± 1.52	7.0 ± 1.1
	Outer	7.04 ± 4.06	2.41 ± 1.51	3.9 ± 1.68	4.3 ± 2.4
NGC 3923	Inner	11.12 ± 3.75	8.77 ± 2.37	8.64 ± 2.38	8.8 ± 2.5
	Outer	8.51 ± 2.21	8.27 ± 0.89	9.18 ± 2.22	8.5 ± 1.9
NGC 4697	Inner	11.55 ± 1.7	11.0 ± 1.95	8.33 ± 2.27	8.4 ± 2.3
	Outer	10.06 ± 2.52	5.96 ± 2.92	4.07 ± 1.35	6.5 ± 2.2
NGC 5044	Inner	9.0 ± 1.02	9.74 ± 1.38	12.56 ± 3.45	10.3 ± 1.9
	Outer	10.09 ± 5.87	10.78 ± 1.23	12.9 ± 6.41	11.3 ± 4.4
NGC 5061	Inner	6.19 ± 1.36	5.14 ± 1.39	4.65 ± 1.23	5.4 ± 1.3
	Outer	5.85 ± 2.75	3.34 ± 1.43	8.56 ± 4.97	5.9 ± 3.0
NGC 5084	Inner	7.28 ± 3.21	6.77 ± 1.81	8.05 ± 1.3	7.4 ± 2.2
	Outer	9.69 ± 1.8	7.23 ± 1.22	5.72 ± 4.84	7.3 ± 2.9
NGC 5152	Inner	12.74 ± 2.38	11.49 ± 3.37	7.08 ± 1.31	10.4 ± 2.4
	Outer	4.66 ± 1.07	8.29 ± 2.1	10.96 ± 1.66	8.1 ± 1.6
NGC 5153	Inner	10.33 ± 1.29	6.92 ± 1.78	5.4 ± 1.42	7.3 ± 1.5
	Outer	9.61 ± 2.41	8.28 ± 1.36	11.96 ± 0.5	10.9 ± 1.0
NGC 5903	Inner	10.39 ± 0.38	10.25 ± 2.49	7.41 ± 2.59	7.7 ± 2.5
	Outer	4.88 ± 0.31	6.99 ± 3.5	9.03 ± 1.43	7.0 ± 1.8
NGC 7252	Inner	0.89 ± 0.18	0.49 ± 0.21	0.08 ± 0.22	0.6 ± 0.2
	Outer	2.71 ± 1.15	0.11 ± 0.07	5.6 ± 2.93	2.7 ± 1.3
NGC 7377	Inner	11.0 ± 4.5	4.22 ± 1.21	5.03 ± 2.43	6.6 ± 2.7
	Outer	10.91 ± 2.65	3.67 ± 1.19	9.82 ± 2.71	8.1 ± 2.2

3.3 Spatially-resolved Stellar Kinematics of the MHONGOOSE Galaxy J1153

As discussed in section 2.2, the methods used to measure the spatially-resolved stellar kinematics of the CLoGS BGEs can similarly be used for the MHONGOOSE galaxy J1153. Since J1153 is much fainter and more difficult to observe than the CLoGS BGEs, several different SALT RSS observations were made for J1153, as listed in Table 2.2. To increase the signal-to-noise ratio of the spectroscopic images obtained for J1153, images of similar resolution and axis orientation were combined. For instance, the two low resolution major axis observations were combined. Similarly, the two low resolution minor axis observations were combined and the two medium resolution major axis observations were combined. The medium resolution minor axis observation need not be combined, since there was only one. This leaves four final images for J1153, i.e. two low resolution images, one for J1153's major axis and one for J1153's minor axis. Similarly, two medium resolution images, one for J1153's major axis and one for J1153's minor axis.

The images that needed to be combined, although very similar to each other, would not have the exact same resolution due to their different observational conditions. Therefore, before these images were combined, they were convolved to exactly match in resolution. The Python code for achieving this is listed in Appendix B.

As discussed in section 2, the spectra for J1153 were extracted similar to that of the CLoGS BGEs. For the major axis observations, spectra are extracted up to 4 kpc and for the minor axis observations, spectra were extracted up to 1 kpc. As with the CLoGS BGEs, we generate stellar velocity dispersion and stellar rotational velocity profiles for each image of J1153. These results are shown in this section. The results are expected to vary, since different resolutions and axis orientations are used for each observation. For instance, one resolution may provide a higher signal-to-noise ratio. Furthermore, the major axis observations would be more physically significant, as most of the stars would be present along the major axis (the extended disc) of the spiral galaxy. Similar to before, we fit stellar velocity dispersion slopes for J1153 with the function:

$$\log(\sigma) = \eta \cdot \log(R) + c \quad c \in \mathbb{R} \quad (3.6)$$

Since we observe J1153 across both its major and minor axes, which differ greatly in size, the stellar velocity dispersion measurements will vary strongly between the different observations. The finding charts of J1153, which show the difference between J1153's major and minor axis, can be found in Appendix A. Therefore, different than Equation 3.1, σ_0 is omitted from Equation 3.6 to more conveniently compare the results for J1153. In this section, we show the low resolution results for J1153's minor axis and the medium resolution results for J1153's major axis. The remaining results can be found in Appendix F.

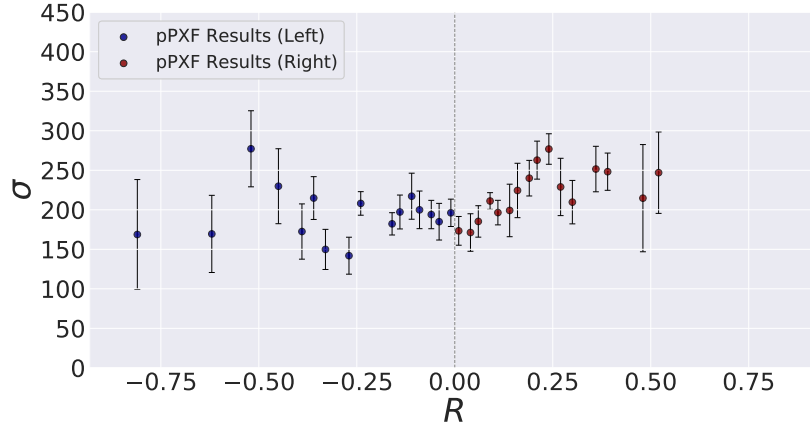


Figure 3.10: Stellar velocity dispersion profile for J1153's minor axis (low resolution).

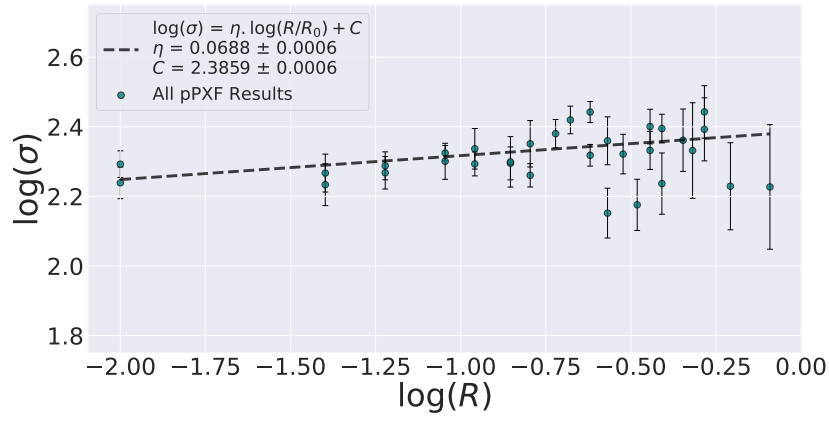


Figure 3.11: Stellar velocity dispersion slope for J1153's minor axis (low resolution). The slope is positive. The profile can be interpreted as increasing with reasonable certainty.

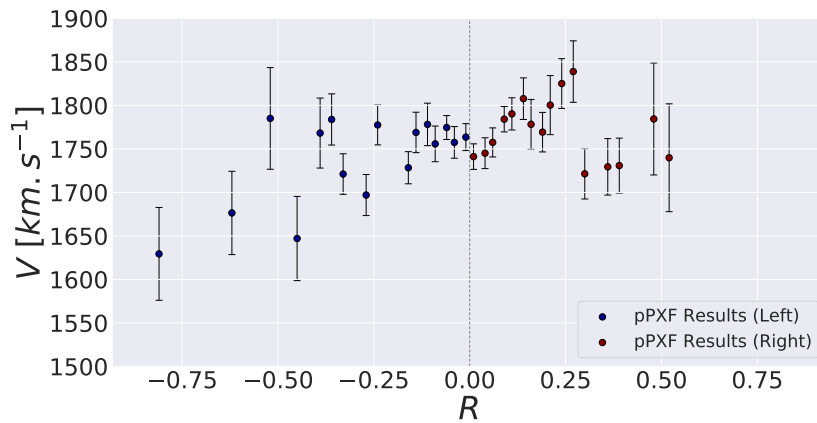


Figure 3.12: Rotational velocity profile of J1153's minor axis (low resolution). The pPXF results show that J1153's minor axis has no clear rotation.

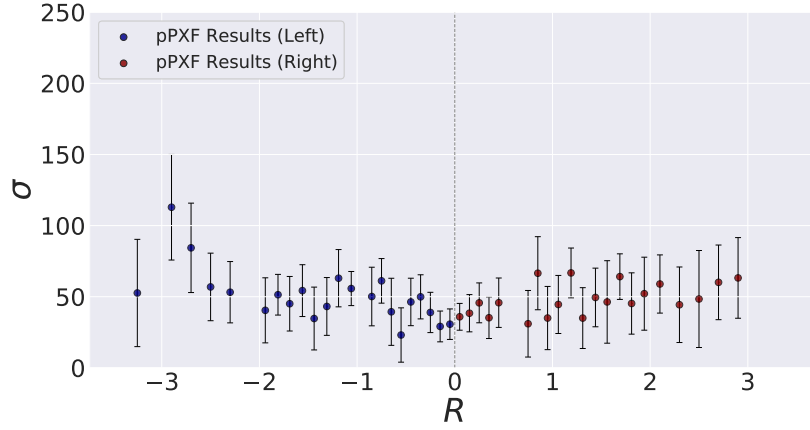


Figure 3.13: Stellar velocity dispersion profile for J1153's major axis (medium resolution).

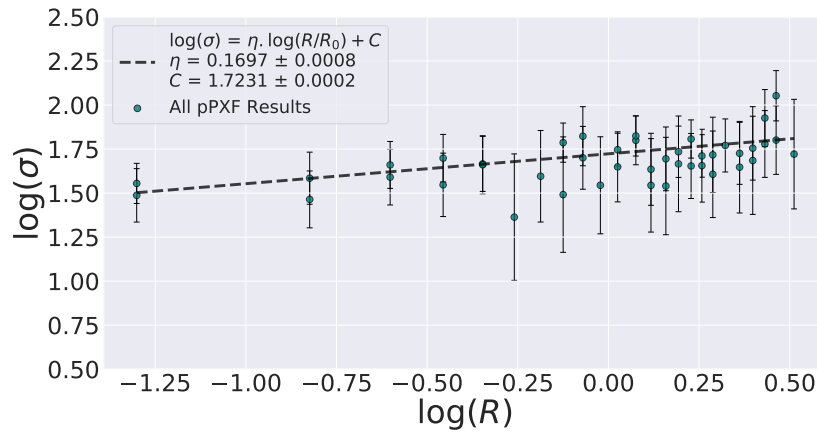


Figure 3.14: Stellar velocity dispersion slope for J1153's major axis (medium resolution). The slope is positive. The profile can be interpreted as increasing with reasonable certainty.

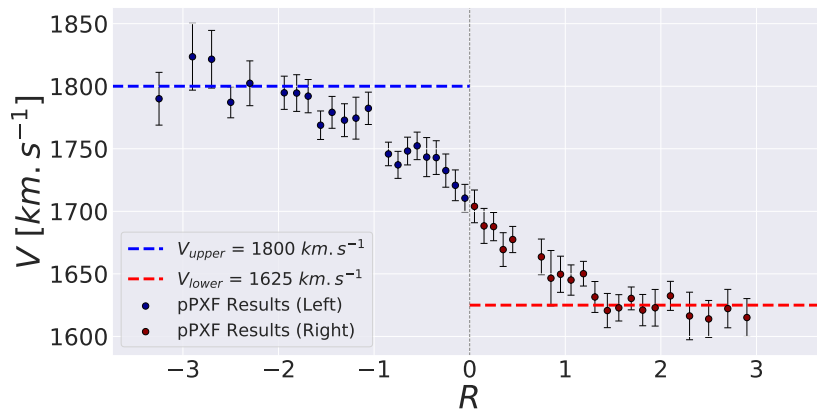


Figure 3.15: Rotational velocity profile of J1153's major axis (medium resolution). The pPXF results show that J1153 has strong rotation along its major axis with $V_{max} = (V_{upper} - V_{lower})/2 \approx 87.5 \text{ km.s}^{-1}$.

3.4 Stellar Populations of the MHONGOOSE Galaxy J1153

As with the CLoGS BGEs, we are interested in the stellar populations of the MHONGOOSE galaxy J1153. Similar to before, we combine the SALT RSS observations of similar resolution and axis orientation together for J1153 to achieve a higher signal-to-noise ratio. This leaves a final spectroscopic image for J1153's major and minor axes, both in low resolution and medium resolution.

The stellar populations of J1153 were measured with FIREFLY, as discussed in section 2.6. The FIREFLY measurements were done for the combined spectroscopic images of J1153.

For the major axis observations of J1153, we extract five spectra with the following apertures:

- An aperture between -0.25 kpc and 0.25 kpc is used to extract a central spectrum.
- An aperture between 0.25 kpc and 1.25 kpc is used to extract a first outer spectrum on the right-hand side. Similarly, an aperture between -0.25 kpc and -1.25 kpc is used to extract a first outer spectrum on the left-hand side.
- An aperture between 1.25 kpc and 4.0 kpc is used to extract a second outer spectrum on the right-hand side. Similarly, an aperture between -1.25 kpc and -4.0 kpc is used to extract a second outer spectrum on the left-hand side.

For the minor axis observations of J1153, we extract three spectra with the following apertures:

- An aperture between -0.25 kpc and 0.25 kpc is used to extract a central spectrum.
- An aperture between 0.25 kpc and 1.0 kpc is used to extract an outer spectrum on the right-hand side. Similarly, an aperture between -0.25 kpc and -1.0 kpc is used to extract an outer spectrum on the left-hand side.

When measuring the stellar populations with FIREFLY, we use the MILES, STELIB, ELODIE and MARCS stellar libraries. For our purposes, we assume a Kroupa IMF when using FIREFLY.

It was found that the combined medium resolution image had the highest signal-to-noise ratio and the most accurate FIREFLY measurements, with a better χ^2_ν statistic, for J1153's minor axis. It was further found that the combined low resolution image had the highest signal-to-noise ratio and the most accurate FIREFLY measurements, with a better χ^2_ν statistic, for J1153's major axis. These results are presented in Appendix G.

We once again calculate the χ^2_ν -weighted ages based on the light-weighted ages measured by FIREFLY, similar to equations 3.3, 3.4 and 3.5, as similarly done for the CLoGS BGEs. In this case however, we use the MILES, STELIB, ELODIE and MARCS stellar libraries which provided the best goodness-of-fit with χ^2_ν close to 1.

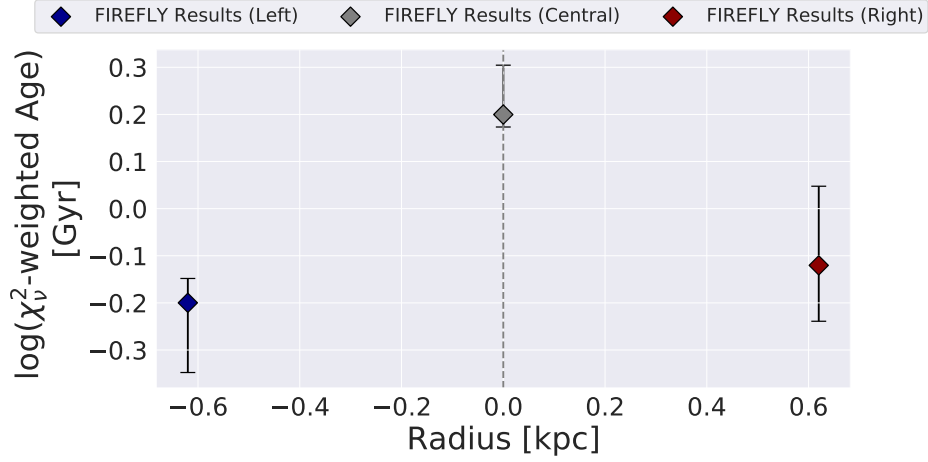


Figure 3.16: χ^2_ν -weighted stellar population ages of J1153's minor axis (low resolution), as measured with FIREFLY.

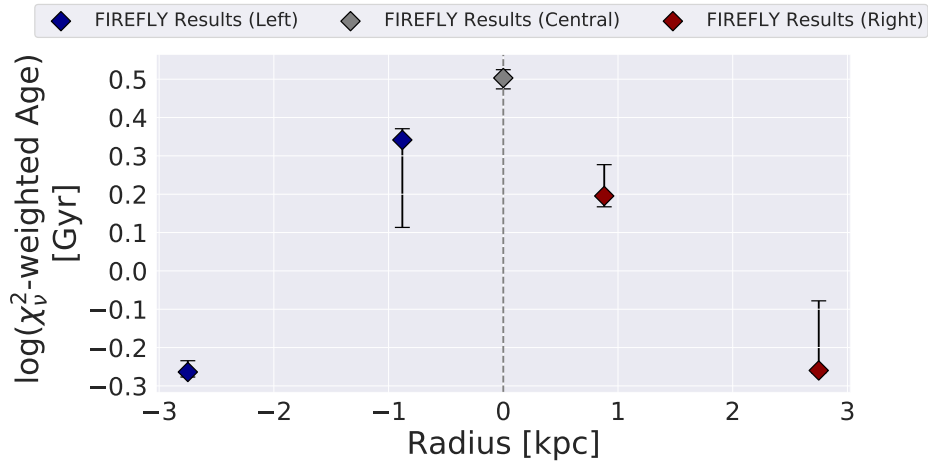


Figure 3.17: χ^2_ν -weighted stellar population ages of J1153's major axis (medium resolution), as measured with FIREFLY.

Similarly as for the CLoGS BGEs, the stellar population ages can be compared with the cold gas content of the galaxy. In more detail, it can be studied how the HI content of J1153 influenced its stellar population history.

In Chapter 4, the spatially-resolved stellar kinematics and stellar populations of the CLoGS BGEs as well as the MHONGOOSE galaxy J1153 will be discussed.

Chapter 4

Discussion

“Somewhere, something incredible is waiting to be known.”

Carl Sagan

In this thesis, we studied the spatially-resolved stellar kinematics and stellar populations of the CLoGS BGEs, as discussed in section 2.1, as well as the MHONGOOSE galaxy J1153, as discussed in section 2.2. The spatially-resolved stellar-kinematics were measured with the full-spectrum fitting software pPXF, and the stellar populations were measured with the full-spectrum fitting software FIREFLY, as discussed in sections 2.5 and 2.6, respectively. These results were finally presented in Chapter 3 and Appendices E to G. In this section the implications of these results will be discussed.

4.1 The CLoGS BGEs

In this section, we discuss the uniqueness of our sub-sample of 18 CLoGS BGEs, by holistically comparing their stellar kinematics with that of other galaxy surveys and galaxy evolution simulations. We further study the stellar populations of these BGEs individually and relate their stellar population ages with their known multi-wavelength properties from catalogues and published literature.

4.1.1 Comparing the Stellar Kinematics with other Galaxy Surveys

As previously discussed in section 1.5.1, the evolutionary paths of BGEs are closely tied to their group environments. Group environments have been found to be more physically complex than previously thought, and this can be observed in the unique stellar kinematics of brightest group galaxies (Brough et al., 2007, Loubser et al., 2022). With regard to

their scaling relations, discussed in section 1.1.4, BGEs are known to fall on a different fundamental plane than ordinary field early-type galaxies (ETGs) (Von Der Linden et al., 2007). Furthermore, BGEs are known to have a steeper Kormendy (size - luminosity) relation, and a steeper Faber-Jackson (velocity dispersion - luminosity) relation, in comparison with field ETGs (Bernardi et al., 2007, Von Der Linden et al., 2007).

BGEs can observationally be distinguished from brightest cluster galaxies (BCGs) using the same scaling relations. To illustrate this, we compare our sub-sample of 18 CLoGS BGEs with the 23 CLoGS BGEs and 32 BCGs studied by Loubser et al. (2018) in Figure 4.1. These BCGs include the Multi-Epoch Nearby Cluster Survey (MENeCS) sample of Sand et al. (2012) and the Canadian Cluster Comparison Project (CCCP) sample of Hoekstra et al. (2015). These nearby BCGs, with a redshift of $z \lesssim 0.3$, complement our sample of nearby CLoGS BGEs, with a redshift of $z \lesssim 0.1$. These BCGs have a luminosity of $-25.7 \text{ mag} \lesssim M_K \lesssim -27.8 \text{ mag}$, and a cluster halo mass between $1.6 \times 10^{14} M_\odot \lesssim M_{500} \lesssim 1.7 \times 10^{15} M_\odot$ (Loubser et al., 2018); whereas the CLoGS BGEs have a luminosity of $-24.2 \text{ mag} \lesssim M_K \lesssim -26 \text{ mag}$, and a group halo mass between $3.6 \times 10^{12} M_\odot \lesssim M_{500} \lesssim 4.4 \times 10^{13} M_\odot$ (Kolokythas et al., 2018).

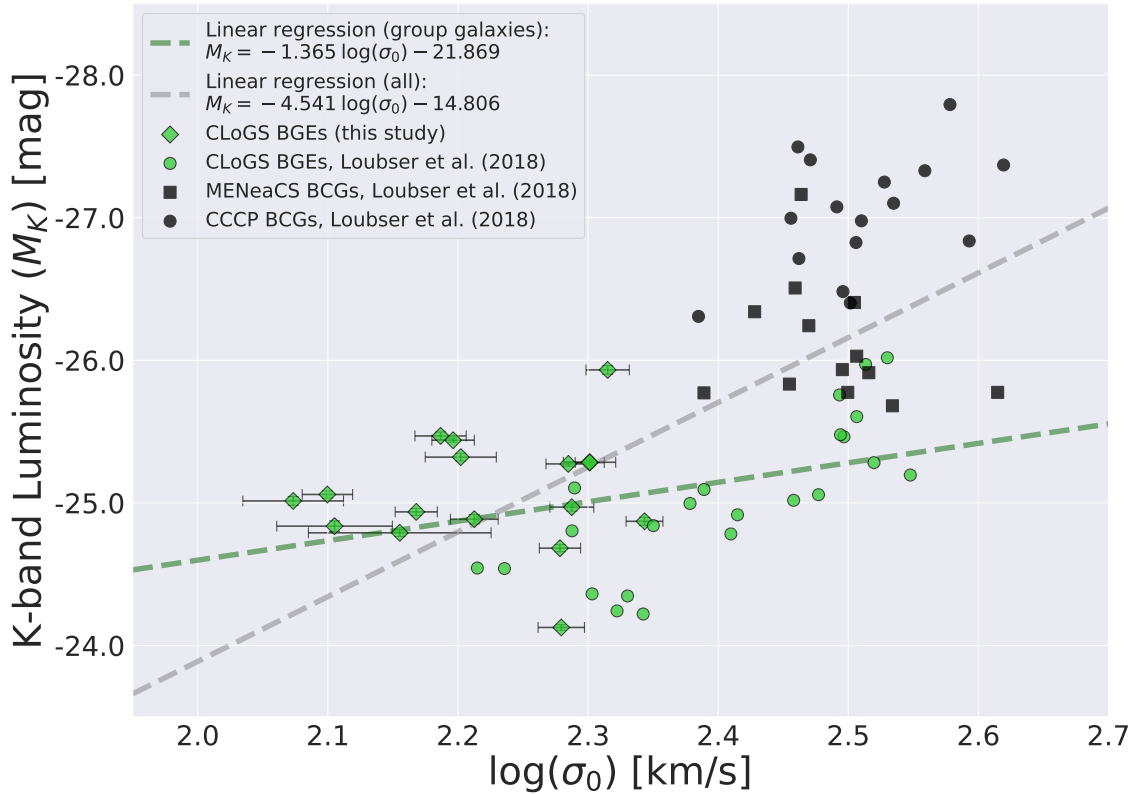


Figure 4.1: Faber-Jackson scaling relation for our selection of galaxies. The CLoGS BGEs from our study and from Loubser et al. (2018) are shown in green. The BCGs from Loubser et al. (2018) are shown in black. We fit linear regression lines through the group galaxies and the entire selection of galaxies separately.

From Figure 4.1, it is clear that the BGEs have a lower central velocity dispersion, σ_0 , which we can attribute to their shallower gravitational potential wells¹. The BGEs are also less luminous in the K-band than the BCGs.

To further study the difference between the CLoGS BGEs, CCCP BCGs and MENeCS BCGs, we can investigate their stellar kinematics in more detail. For instance, we can compare their degree of stellar rotation by comparing their anisotropy parameters V_{max}/σ_0 . Where V_{max} is the maximum degree of rotation, and σ_0 is the central velocity dispersion, as defined in section 3.1. The anisotropy parameter and ellipticity ϵ of these galaxies determine whether or not these galaxies are rotationally supported or pressure supported systems as previously discussed in section 1.2.1. We present these results in Figure 4.2.

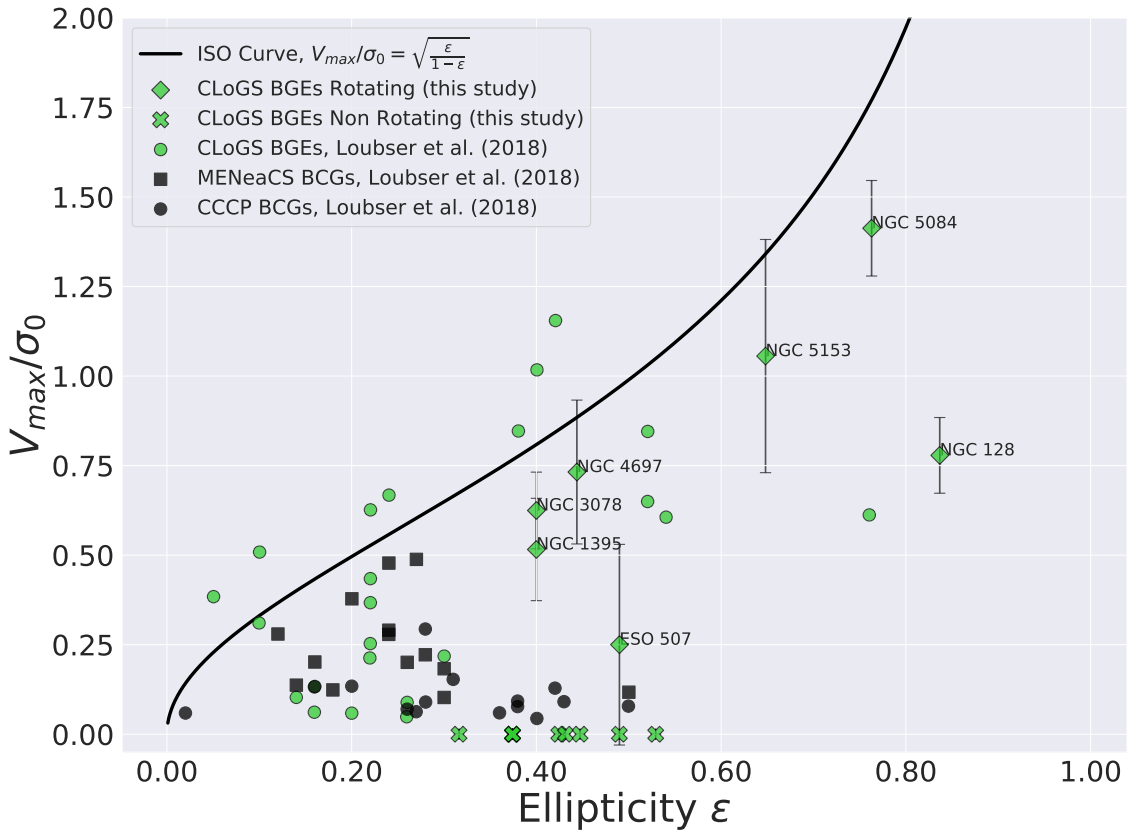


Figure 4.2: Anisotropy parameter (V_{max}/σ_0) versus ellipticity (ϵ). The solid line, labelled as “ISO Curve” shows the predicted rotation for an edge-on-observed oblate spheroid (Bender et al., 1992). rotationally supported galaxies fall on or above the ISO curve and pressure supported galaxies fall below. The CLoGS BGEs from our study and from Loubser et al. (2018) are shown in green. The marginally rotating CLoGS BGEs are labelled by name; however, none are rotationally supported.

¹Although redshift may influence these results, the redshift between the BGEs and BCGs are comparatively similar and unlikely to be the primary cause of this result.

From Figure 4.2, it can be seen that seven out of the 18 CLoGS BGEs from our sub-sample show a marginal degree of stellar rotation, with $V_{max}/\sigma_0 > 0$. The strongest rotating BGEs from our sub-sample include NGC 128, NGC 4697, NGC 5084 and NGC 5153, with $V_{max}/\sigma_0 \gtrsim 0.75$. However, it cannot be said for certain that any of the 18 CLoGS BGEs from our sub-sample are rotationally supported, since all 18 BGEs fall below the ISO curve. It is known that the inclination angle of early-type galaxies may influence their observed anisotropy parameters (Burkert and Naab, 2005). However, within our error margins, the CLoGS BGEs would remain pressure supported systems and not rotationally supported systems.

Finally, the velocity dispersion slopes of the CLoGS BGEs, as calculated in section 3, can be compared with that of the CCCP- and MENeACS-BCGs as well as other complementary ETG samples. This is shown in Figure 4.3. Similar to Loubser et al. (2018), we compare our results against the ETG samples of Cappellari et al. (2006) and Mehlert et al. (2000).

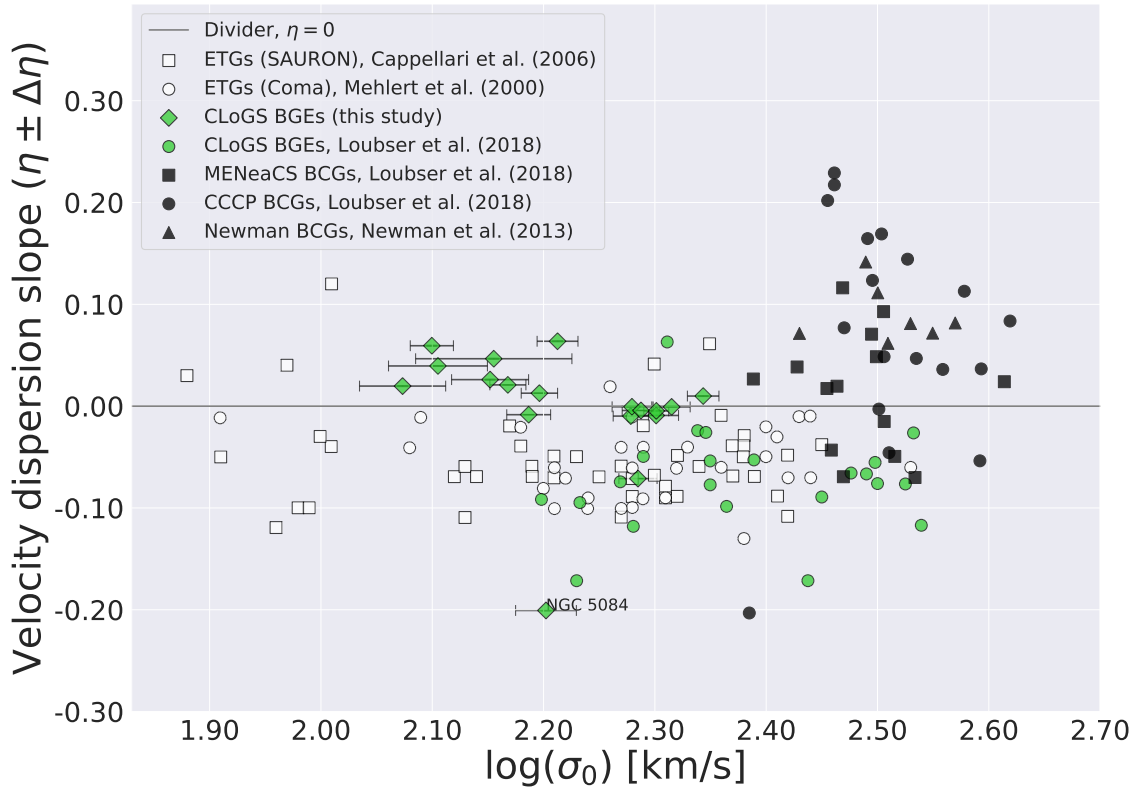


Figure 4.3: Velocity dispersion slope ($\eta \pm \Delta\eta$) versus central velocity dispersion (σ_0). The ETGs from Cappellari et al. (2006) and Mehlert et al. (2000) are shown in white. The CLoGS BGEs from our study and from Loubser et al. (2018) are shown in green. The BCGs from Loubser et al. (2018) and Newman et al. (2013) are shown in black.

From Figure 4.3, it is clear that the majority of our sub-sample of 18 CLoGS BGEs has a

nearly flat velocity dispersion slope of $-0.10 \lesssim \eta \lesssim 0.10$, save NGC 5084. It can further be seen from Figure 4.3 that the BCGs have a notably higher central velocity dispersion and velocity dispersion slope than the CLoGS BGEs and the field ETGs. Furthermore, the stellar kinematics of the CLoGS BGEs more closely resemble the ETG samples than the BCG samples. More specifically, the CLoGS BGEs have similar velocity dispersion slopes to the ETGs in the central velocity dispersion range $2.1 \lesssim \log(\sigma_0) \lesssim 2.4$. It is known that the velocity dispersion of a central galaxy is tied to the mass of its dark matter halo (Zahid et al., 2018). The velocity dispersion slopes of the BGEs can be used as a proxy for its dynamical mass, which, in turn, can be used to study the mass-assembly histories of these galaxies (Loubser et al., 2020; Loubser et al., 2021). These aforementioned results suggest that the mass-assembly histories of the CLoGS BGEs may be more similar to field ETGs.

The comparisons that we have made in this section show that the CLoGS BGEs are truly unique in their stellar kinematics, showing a variety of different anisotropy parameters, central velocity dispersions and velocity dispersion slopes. This information is ultimately useful for building galaxy evolution models. These models help us understand the underlying astrophysics of group environments, such as their dark matter content, baryonic processes, and hydrodynamics. These models can be tested against observational results such as ours. In section 4.1.2, we compare our observational results with some of the latest galaxy evolution simulations.

4.1.2 Comparing the Stellar Kinematics with Galaxy Evolution Simulations

Observationally, the stellar kinematics of central group galaxies and central cluster galaxies are fundamentally different, as we have shown in section 4.1.1; however, the exact difference between galaxy groups and galaxy clusters is still poorly defined (Mo et al., 2010). Galaxy groups have been viewed as scaled-down versions of galaxy clusters, containing fewer member galaxies; however, there is no clear consensus on what exactly differentiates a galaxy group from a galaxy cluster (Tully, 2015). For instance, it is unclear what the exact size of a galaxy group needs to be, or exactly how many member galaxies it needs to contain. Certain numbers have been suggested, but these definitions lack astrophysical foundation (Tully, 2015). In the hierarchical model of galaxy evolution, discussed in detail in section 1.1.3, galaxy clusters may form from the merging of galaxy groups (Bosch et al., 2014). Therefore, to understand the formation of galaxy clusters, the evolution of galaxy groups and the transition from galaxy group to galaxy cluster need to be studied in more detail.

Recent studies have found that galaxy groups are more than just an intermediary environment between fields and galaxy clusters (Oppenheimer et al., 2021). Galaxy groups

have been found to exhibit a unique range of baryonic and hydrodynamic processes, different to that of field haloes and galaxy clusters (Oppenheimer et al., 2021). These processes are fundamental to galaxy evolution, and therefore galaxies will evolve radically different in group environments than in fields or clusters. It has further been shown that AGN and stellar feedback, which are prevalent in galaxy clusters (e.g. McNamara and Nulsen, 2007), also play a role in galaxy groups (Kolokythas et al., 2018). These effects may possibly play a greater role in the formation of brightest group galaxies, which are highly susceptible to these effects (Kolokythas et al., 2018).

With the dramatic improvement in computational power achieved over the last few decades, cosmological simulations have become increasingly useful in modeling the complex evolution, star-formation and feedback mechanisms of galaxies within groups and clusters (Vogelsberger et al., 2020). Recent galaxy evolution simulations, such as DIANOGA by Bassini et al. (2020), and Romulus by Tremmel et al. (2017), are some of the most recent attempts to simulate the stellar kinematics of central group galaxies and central cluster galaxies in the nearby Universe. These simulations take into account several factors, such as the possible mass of the galaxy’s dark matter halo, the star-formation rate of the galaxy, and the rate at which gas cools within the galaxy (Jung et al., 2022). These simulations further attempt to model the complicated AGN- and stellar feedback mechanisms of these galaxies, which play a prominent role in the evolution of these galaxies (Puchwein et al., 2008). The Romulus suite of simulations, in particular, present a novel way of modeling supermassive black hole (SMBH) accretion and feedback for low redshift ($z \sim 0$) central group galaxies (Tremmel et al., 2017). In addition, the DIANOGA simulation models the unique star-formation and hydrodynamical processes of protoclusters in the low to medium redshift Universe ($0 \lesssim z \lesssim 4$).

In this section, we briefly compare the stellar kinematics that we observe for the CLoGS BGEs with these simulations. This is shown in Figure 4.4. The purpose of doing so is to provide additional observational data for those building and improving galaxy evolution models.

The Romulus suite of simulations assume a Λ CDM Universe with cosmological parameters: $\Omega_m = 0.309$, $\Omega_\Lambda = 0.691$, $\Omega_b = 0.0486$, $H_0 = 67.8 \text{ km.s}^{-1}.\text{Mpc}^{-1}$ and $\sigma_8 = 0.82$ (Tremmel et al., 2017; Jung et al., 2022). The 107 Romulus BGGs, that we compare our observational data with, are summarised in Jung et al. (2022). 47 of these BGGs have a halo mass of $12 \leq \log(M_{200}/M_\odot) < 12.5$ (Jung et al., 2022). These BGGs will be referred to as the Romulus (Light) sample in Figure 4.4. 60 of these BGGs have a halo mass of $\log(M_{200}/M_\odot) \geq 12.5$ (Jung et al., 2022). These BGGs will be referred to as the Romulus (Heavy) sample in Figure 4.4. The DIANOGA simulation similarly assumes a Λ CDM Universe with cosmological parameters: $\Omega_m = 0.24$, $\Omega_b = 0.037$, $H_0 = 72 \text{ km.s}^{-1}.\text{Mpc}^{-1}$ and $\sigma_8 = 0.8$ (Bassini et al., 2020). The 60 BCGs that we will compare our observational

data with are summarised in Marini et al. (2021).

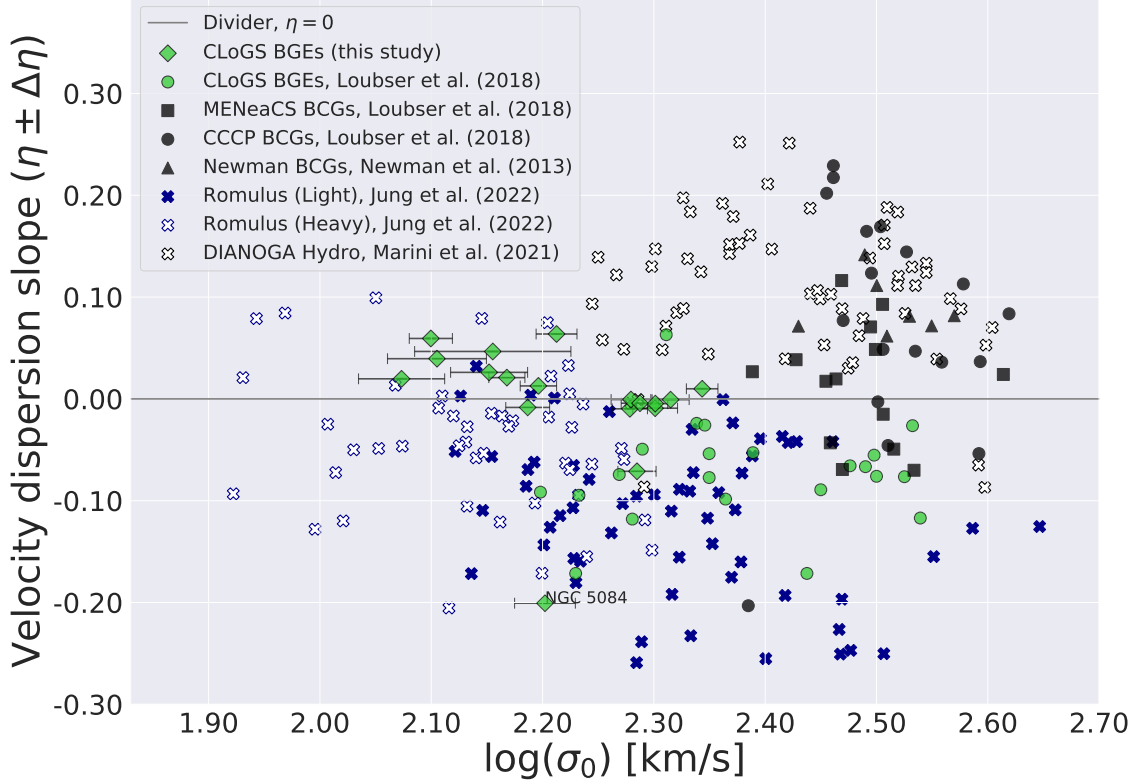


Figure 4.4: Velocity dispersion slope ($\eta \pm \Delta\eta$) vs. central velocity dispersion (σ_0). The CLoGS BGEs are shown in green. The ETGs from Cappellari et al. (2006) and Mehlert et al. (2000) are shown in white. The BCGs from Loubser et al. (2018) and Newman et al. (2013) are shown in black. The results are compared with the latest simulation results: Romulus, as used by Jung et al. (2022), shown in blue, and DIANOGA Hydro, as used by Marini et al. (2021), shown in white.

From Figure 4.4, it can be seen that the range of velocity dispersion slopes, η , which we observe for the CLoGS BGEs, differ from that of the Romulus BGGs and DIANOGA Hydro BCGs. In contrast with the Romulus simulations, which predict $-0.3 \lesssim \eta \lesssim 0.1$, and the DIANOGA Hydro simulation, which predict $-0.1 \lesssim \eta \lesssim 0.3$, we observe $-0.1 \lesssim \eta \lesssim 0.1$ for the majority of the CLoGS BGEs. Therefore, it is uncertain whether current galaxy evolution simulations can reproduce the stellar kinematics we observe for the CLoGS BGEs.

4.1.3 Stellar Populations

In the hierarchical model of galaxy evolution, discussed in section 1.1.3, early-type galaxies are theorised to form from the prior merging of late-type galaxies. This theory is still held today (De Lucia et al., 2006; Bosch et al., 2014). Conventionally, the central, dominant early-type galaxies of galaxy groups and clusters have been thought of as passively evolving systems with little to no ongoing star-formation. It was thought that the interstellar material needed to form new stars would have been stripped when galaxies merge and form early-type galaxies. This notion dates as far back as the 1950s (Spitzer Jr and Baade, 1951).

Nearby early-type galaxies of low redshift ($z \lesssim 1$) have in the past been referred to as “red and dead” galaxies with little to no ongoing star-formation (Romeo et al., 2008; Brammer et al., 2009). These galaxies have been thought of as homogeneous systems, only containing an old stellar population (Ellis et al., 1997; Andreon, 2003; De Lucia et al., 2004). However, several new studies have shown that these early-type galaxies have a sufficient supply of cold gas to form new stars and to host a young stellar population (Bildfell et al., 2008; Loubser et al., 2016; Oppenheimer et al., 2021).

In section 3 and Appendix E, we presented the stellar population properties of our subsample of 18 CLoGS BGEs, as measured with FIREFLY, and discussed in section 2.6. Recent multi-wavelength studies such as O’Sullivan et al. (2015) and O’Sullivan et al. (2018a) have measured the cold gas supply of these galaxies, such as their CO and HI content. In addition, the radio and X-ray properties of the CLoGS BGEs are known. This includes information about the AGN activity prevalent in some of the CLoGS BGEs (Kolokythas et al., 2018). A summary of this information is provided in Table 4.1. Table 4.1 includes the χ^2_ν -weighted ages of the CLoGS BGEs, as calculated with equations 3.3 to 3.5. These χ^2_ν -weighted ages provide an indication of the average age of the stellar populations in the inner and outer regions of the CLoGS BGEs. This, in addition with the multi-wavelength information available for the CLoGS BGEs, can be used to verify whether or not the CLoGS BGEs have young stellar populations within their systems. It is further discussed what may cause or prevent young stellar populations from forming within these systems, and what multi-wavelength information supports the stellar populations we observe.

In this section, we will consider each CLoGS BGE individually, discussing their unique stellar population properties and available multi-wavelength information, respectively. For the sake of completeness, NGC 2293, the close neighbouring galaxy of NGC 2292, and NGC 5152, the close neighbouring galaxy of NGC 5153, will be included in our analysis.

Table 4.1: Multi-wavelength properties of the CLoGS-BGEs. The Richness parameter ‘R’ refers to number of optically bright galaxies in the group (O’Sullivan et al., 2017). The X-ray and radio morphologies are from the multi-wavelength studies of Kolokythas et al. (2018) and Kolokythas et al. (2019). Information for NGC 1550 and NGC 5903 can be found in Kolokythas et al. (2020) and O’Sullivan et al. (2018b), respectively. The X-ray analysis of the low-richness sub-sample is still incomplete. The cold gas measurements are from O’Sullivan et al. (2015) and O’Sullivan et al. (2018a). The far-ultraviolet (FUV) star-formation rates SFR_{FUV} are from Kolokythas et al. (2022) and the far-infrared (FIR) star-formation rates are from O’Sullivan et al. (2015) and O’Sullivan et al. (2018a).

Galaxy	Morphology	R	X-ray morphology	Radio morphology	Cold gas	χ^2_ν -weighted age (Gyr) (Inner region)	χ^2_ν -weighted age (Gyr) (Outer region)	SFR_{FUV} $\pm 5\%$ ($M_\odot.yr^{-1}$)	SFR_{FIR} ($M_\odot.yr^{-1}$)
ESO 507-25	-3.0, E/S0	4	galaxy-like	diffuse	HI (probable disc)	6.5 ± 2.0	7.5 ± 3.8	0.221	-
NGC 128	-2.0, S0	3	-	point-like	CO(1-0), CO(2-1), HI(cloud)	4.0 ± 1.5	4.5 ± 1.3	0.049	1.193 ± 0.085
NGC 193	-3.0, E	7	group-like	large-scale jet	CO(1-0), CO(2-1)	9.3 ± 3.7	8.9 ± 1.8	0.047	-
NGC 1395	-4.8, E	3	-	point-like	CO(2-1)	7.3 ± 2.5	5.3 ± 2.7	0.042	0.023 ± 0.005
NGC 1550	-4.1, E	2	group-like	large-scale jet	CO(1-0), CO(2-1)	9.2 ± 1.6	12.2 ± 2.4	0.083	-
NGC 2292	-2.0, S0	3	-	-	CO(2-1)	3.7 ± 0.9	6.5 ± 2.4	-	0.314 ± 0.022
NGC 2293	-1.0, S0a	3	-	-	-	8.7 ± 3.5	6.7 ± 1.4	-	-
NGC 2911	-2.0, S0	3	-	point-like	CO, H ₂ (misaligned disc)	7.2 ± 3.3	5.0 ± 1.6	0.032	0.117 ± 0.020
NGC 3078	-4.7, E	6	galaxy-like	diffuse	CO(2-1)	10.5 ± 2.5	9.5 ± 4.0	0.024	-
NGC 3325	-4.9, E	3	-	-	CO(1-0), CO(2-1)	7.0 ± 1.1	4.3 ± 2.4	0.015	-
NGC 3923	-4.7, E	2	-	point-like	CO(2-1)	8.8 ± 2.5	8.5 ± 1.9	0.042	0.004 ± 0.001
NGC 4697	-4.4, E	3	-	point-like	-	8.4 ± 2.3	6.5 ± 2.2	0.031	-
NGC 5044	-4.8, E	5	group-like	remnant	Sub-kpc CO clouds	10.3 ± 1.9	11.3 ± 4.4	0.073	0.079
NGC 5061	-4.3, E	3	-	point-like	CO(2-1)	5.4 ± 1.3	5.9 ± 3.0	0.027	0.004 ± 0.001
NGC 5084	-2, S0	4	galaxy-like	point-like	CO(2-1), HI (disc)	7.4 ± 2.2	7.3 ± 2.9	0.045	0.128 ± 0.016
NGC 5152	2.7, SBb	7	galaxy-like	-	-	10.4 ± 2.4	8.1 ± 1.6	-	-
NGC 5153	-4.8, E	7	galaxy-like	-	CO(2-1)	7.3 ± 1.5	10.9 ± 1.0	0.013	-
NGC 5903	-4.7, E	3	group-like	diffuse	CO(2-1), HI	7.7 ± 2.5	7.0 ± 1.8	0.011	-
NGC 7252	-2.0, S0	2	-	point-like	HI (tidal tails and disc)	0.6 ± 0.2	2.7 ± 1.3	0.368	8.1
NGC 7377	-1.0, S0/a	2	-	point-like	-	6.6 ± 2.7	8.1 ± 2.2	0.060	0.509 ± 0.062

ESO 507-25: ESO 507-25 is regarded as an actively star-forming galaxy with a notable supply of cold gas with $M(\text{H}_2) = 4.23 \pm 0.56 \text{ M}_\odot$, and $\log(M(\text{HI})) = 10.50 \text{ M}_\odot$ (e.g. O’Sullivan et al., 2018a), and a high star-formation rate of $SFR_{FUV} = 0.221 \text{ M}_\odot.\text{yr}^{-1}$ (Kolokythas et al., 2022). The cold gas is observable by the galaxy’s broad CO emission lines (e.g. Knapp and Rupen, 1996) as well as its double-peaked HI line profile (e.g. O’Sullivan et al., 2018a). ESO 507-25 is known to be a radio-quiet galaxy with $P_{1.4 \text{ GHz}} < 10^{23} \text{ W.Hz}^{-1}$, and with diffuse radio emission observable at 610 MHz (Kolokythas et al., 2018). It is believed that ESO 507-25’s diffuse radio emission is associated with its star formation (Olivares et al., 2022). We measure a χ_ν^2 -weighted age of $\sim 6 \text{ Gyr}$ for ESO 507-25’s inner and outer region. This implies that ESO 507-25 has experienced ongoing star-formation with a partly young stellar population distributed through its inner and outer region, consistent with O’Sullivan et al. (2018a), Kolokythas et al. (2022), Olivares et al. (2022) and Lagos et al. (2022).

NGC 128: NGC 128 has a fair amount of cold gas of $M(\text{H}_2) = 1.76 \pm 0.18 \text{ M}_\odot$, and $\log(M(\text{HI})) = 8.65 \text{ M}_\odot$ (O’Sullivan et al., 2018a). An extensive HI cloud covers half of NGC 128 as well as its close neighbouring galaxy NGC 127 (Chung et al., 2012; O’Sullivan et al., 2018a). The velocity profile of the HI cloud indicates that the cold gas originates from NGC 128 itself (O’Sullivan et al., 2018a). NGC 128 is known to have some dust-obscured star formation, with $SFR_{FIR} = 1.193 \pm 0.085$ (O’Sullivan et al., 2018a). We measure a χ_ν^2 -weighted age of $\sim 4 \text{ Gyr}$ for NGC 128’s inner and outer region. This is a reasonable estimate based on NGC 128’s cold gas supply and star formation rate.

NGC 193: NGC 193 is a radio-loud galaxy with an active radio jet of $P_{1.4 \text{ GHz}} = 11.1 \pm 0.6 \times 10^{23} \text{ W.Hz}^{-1}$ (Kolokythas et al., 2018). NGC 193 has a low amount of cold gas with $M(\text{H}_2) < 1.35 \times 10^8 \text{ M}_\odot$ (O’Sullivan et al., 2018a). The AGN jet may heat the intragalactic medium of NGC 193, removing cold gas from its system, and quenching star-formation within the galaxy (Fabian, 2012; Kolokythas et al., 2018). Kolokythas et al. (2022) further report a very low star-formation rate for NGC 193, which indicates that AGN-feedback may have limited NGC 193’s star-formation. We measure old stellar populations for NGC 193, with a χ_ν^2 -weighted age $\sim 9 \text{ Gyr}$ for its inner and outer regions. This further supports the notion that AGN-feedback has limited younger stars from forming in NGC 193.

NGC 1395: NGC 1395 is the BGE of LGG 097 (the Eridanus supergroup). NGC 1395 is cold gas deficient (O’Sullivan et al., 2018a), and it has been suggested that tidal interactions and galaxy harassment in the Eridanus supergroup may be responsible for this deficiency (Murugesan et al., 2021). A deep Gemini-South/GMOS optical study of NGC 1395’s structure has suggested that NGC 1395 has experienced a recent merger event (Escudero et al., 2018). This merging event may account for NGC 1395’s unique structure

and stellar population. Furthermore, NGC 1395’s spectroscopic data suggests that NGC 1395 hosts an older stellar population in its central region (Escudero et al., 2018). Our spectroscopic results suggest the same in which we measure a χ_ν^2 -weighted age ~ 7 Gyr for NGC 1395’s inner region and a χ_ν^2 -weighted age ~ 5 Gyr for NGC 1395’s outer region. However, the outer region of NGC 1395 may be older, based on the χ_ν^2 statistics of the FIREFLY fits.

NGC 1550: NGC 1550 is the BGE of the galaxy group LGG 133, which is a known fossil galaxy group (Jones and Forman, 1984). NGC 1550 is further known to exhibit AGN-feedback and sloshing, which further prevent new stars from forming (Kolokythas et al., 2020; Kolokythas et al., 2022). Unsurprisingly, we measure very old stellar populations for NGC 1550’s inner and outer region. In particular, we measure a χ_ν^2 -weighted age ~ 12 Gyr for NGC 1550’s outer region with reasonably good χ_ν^2 statistics, especially with the ELODIE stellar library.

The NGC 2292/2293 galaxy pair: The CLoGS BGE 2293 and its close neighbour NGC 2292 are remarkably unique. These two galaxies are strongly gravitationally bound, and very similar in luminosity, as well as in morphology (Temi et al., 2004). HI emission is detected in neither of the two galaxies, rather an HI ring encompasses the NGC 2292/2293 galaxy pair (Stickel et al., 2005). This is a highly unusual structure that has only been observed in a handful of sources (Stickel et al., 2005). The HI ring spans over ~ 17 Mpc with a total mass of $M(\text{HI}) \approx 0.75 \times 10^9 M_\odot$ and $M(\text{H}_2) \approx 7 \times 10^7 M_\odot$ (Barnes, 1999; Stickel et al., 2005). Caution is advised as galaxy pairs such as NGC 2292/2293 are still poorly understood (Kolokythas et al., 2022). We detect stellar populations of intermediate age for NGC 2292/2293. In particular, we measure a χ_ν^2 -weighted age ~ 9 Gyr for NGC 2293, with fair χ_ν^2 statistics using the MILES and STELIB stellar libraries.

NGC 2911: NGC 2911 has a notable supply of cold gas within an H_2 disc (O’Sullivan et al., 2018a). The stellar kinematics of NGC 2911 is known to be misaligned with its H_2 disc, suggesting that the cold gas has an external origin, or is outwardly cooled (O’Sullivan et al., 2018a). We further detect that the stellar population of NGC 2911’s outer region, with a χ_ν^2 -weighted age of ~ 5 Gyr, is younger than NGC 2911’s inner region, with a χ_ν^2 -weighted age of ~ 7 Gyr. A high degree of trust can be placed in these values based on the excellent χ_ν^2 statistics obtained across the MILES, STELIB and ELODIE stellar libraries. Since there is more cold gas within the outskirts of NGC 2911, it is not unlikely to detect a younger stellar population in the outer region of NGC 2911.

NGC 3078: NGC 3078 hosts a moderately strong radio AGN with diffuse emission of ~ 310 mJy at 1.4 GHz, as well as a nuclear dust disc (Kolokythas et al., 2018). The nature

of the NGC 3078’s AGN and morphology suggest that its radio jet has been disrupted (Kolokythas et al., 2018). NGC 3078 has a low supply of cold gas with $M(\text{H}_2) < 0.23 \times 10^8 M_\odot$, and a low star-formation rate of $SFR_{FUV} = 0.024 M_\odot \cdot \text{yr}^{-1}$ (Kolokythas et al., 2022). We measure old stellar populations for NGC 3078 with χ_ν^2 -weighted age ~ 10 Gyr for its inner and outer regions. Similar to NGC 193, we assume that AGN-feedback has quenched star-formation to some degree in the galaxy’s history (Fabian, 2012; Kolokythas et al., 2018).

NGC 3325: NGC 3325 is the least studied galaxy out of our sub-sample of CLoGS BGEs. NGC 3325 is undetected in the radio band, except for a tentative 1 ± 3 mJy signal measured by Arecibo at 2.38 GHz in the past (Dressel and Condon, 1978; Kolokythas et al., 2019). We further know little of NGC 3325’s cold gas content, apart from that it contains some amount of cold gas with $\log(M(\text{HI})) \approx 9.18 M_\odot$.

NGC 3923: NGC 3923 is a well-known shell galaxy theorised to have formed from a major merging event (Carlsten et al., 2017). We measure old stellar populations for NGC 3923 with a χ_ν^2 -weighted age ~ 8.5 Gyr for its inner and outer regions. In particular, we obtain excellent statistics when fitting NGC 3923’s outer region with $\chi_\nu^2 \sim 1$ across MILES, STELIB and ELODIE. The stellar population age we measure for NGC 3923’s outer region is slightly lower than the age of 10 Gyr measured by (Carlsten et al., 2017), but within our error margins. In contrast with Carlsten et al. (2017), we do not observe a positive age gradient (i.e. the stellar population of NGC 3923 becomes older with radius). Additional observations of NGC 3923’s outer shells may provide further insight.

NGC 4697: Similar to a recent optical spectroscopic study by Feldmeier-Krause et al. (2021), we report stellar populations with ages < 9 Gyr for NGC 4697. In more detail, we report χ_ν^2 -weighted ages of 8.4 ± 2.3 Gyr and 6.5 ± 2.2 Gyr for NGC 4697’s inner and outer region, respectively. NGC 4697 has low chemical enrichment, indicating that the galaxy has a slower initial star-formation rate (Feldmeier-Krause et al., 2021). Kolokythas et al. (2022) confirm a low star-formation rate for NGC 4697. NGC 4697 is further known to have a diffuse molecular gas disc of $1.6 \times 10^7 M_\odot$ associated with its SMBH (Davis et al., 2017). Although no HI or CO is detected for NGC 4697, the galaxy features polycyclic aromatic hydrocarbons (PAHs) (Ford and Bregman, 2013). It has been proposed that PAHs are associated with the stellar winds from intermediate stellar populations (Vega et al., 2010). Additionally, PAHs may potentially be linked to recent star-formation (Vega et al., 2010). However, the lack of cold gas detected for NGC 4697 (O’Sullivan et al., 2018a), as well as the intermediate stellar population ages we detect for NGC 4697, suggests that the PAHs are associated with stellar winds.

NGC 5044: NGC 5044 is the only CLoGS BGE from our sub-sample with strong evidence of cooling flows; gas condensation from its intragalactic medium (IGM) (O’Sullivan et al., 2018a; Kolokythas et al., 2022). NGC 5044 is known to have a remnant radio-jet, and it has been suggested that NGC 5044 is at the start of a new AGN-feedback cycle (Kolokythas et al., 2018; Schellenberger et al., 2020). We measure very old stellar populations for NGC 5044. We suggest that AGN-feedback may have prevented new stars from forming within the galaxy.

NGC 5061: Similar to Feldmeier-Krause et al. (2021), we detect a stellar population age of ~ 5 Gyr for NGC 5061, suggesting a younger stellar population component. A more detailed study of NGC 5061’s stellar population history may provide further insight.

NGC 5084: It is believed that NGC 5084 merged with an HI-rich dwarf galaxy in its recent history (Kolokythas et al., 2018). This is evident from the galaxy’s distorted inner region, as well as its high concentration of HI (Kolokythas et al., 2018). NGC 5084 is on par with ESO 507-25 as one of the CLoGS BGEs with the highest HI mass with $\log(M(\text{HI})) = 10.18 M_{\odot}$. The stellar population ages we measure for NGC 5084 are similar to that of ESO 507-25; however, the FIREFLY fits for NGC 5084 have slightly poorer χ^2_{ν} statistics. Furthermore, NGC 5084 has a lower star-formation rate (Kolokythas et al., 2022). The lower star-formation rate can be explained by NGC 5084’s lower amount of H_2 , with a mass of $M(\text{H}_2) < 0.16 \times 10^8 M_{\odot}$ (O’Sullivan et al., 2018a), which is a more important ingredient for star-formation (Leroy et al., 2008).

The NGC 5152/5153 galaxy pair: NGC 5153 is the BGE of the galaxy group LGG 351. It has been suggested that LGG 351 is a fossil group, an isolated and dynamically old group with little star-formation (e.g. Jones and Forman, 1984), in its early evolutionary stages (Henriksen, 2021). We measure an old stellar population for NGC 5153’s outer region, with a χ^2_{ν} -weighted age ~ 11 Gyr. It is believed that dynamically young groups, such as LGG 351, evolve into fossil groups after several of its member galaxies have undergone merging events, such as the NGC 5152/5153 galaxy pair, which will soon merge (Henriksen, 2021). The lack of cold gas for NGC 5152/5153 (O’Sullivan et al., 2018a), their very low star-formation rates (Kolokythas et al., 2022), and the old stellar populations which we measure for NGC 5152/5153 further suggest that LGG 351 may plausibly evolve into a fossil group in the future.

NGC 5903: NGC 5903 has a highly unusual structure, in which a ~ 110 kpc HI filament crosses the galaxy (O’Sullivan et al., 2018b). Furthermore, an unknown diffuse radio source of ~ 75 kpc, partly enclosed by the HI filament, covers the galaxy (O’Sullivan et al., 2018b). NGC 5903’s unique structure is theorised to originate from an interaction-

triggered AGN outburst, and from high-velocity collisions between the galaxy, the HI filament and/or other member galaxies (Kolokythas et al., 2019). NGC 5903 is thought to be passively evolving after the AGN outburst (with cold galaxies leaving the galaxy), and in the later stages of its evolution (O’Sullivan et al., 2018b). We measure stellar populations of intermediate age for NGC 5903.

NGC 7252: NGC 7252 is a post-merger starburst galaxy, for which we can expect a high star-formation rate as well as a very large young stellar population (Dopita et al., 2002). Unsurprisingly, NGC 7252 has a vast amount of cold gas, with $M(\text{H}_2) = 58.0 \pm 8.7 \text{ M}_\odot$ and $\log(M(\text{HI})) = 9.61 \text{ M}_\odot$ (O’Sullivan et al., 2018a). NGC 7252 has the largest supply of cold gas out of our sub-sample of CLoGS BGEs. Furthermore, NGC 7377 has the highest star-formation rate out of our sub-sample with $SFR_{FUV} = 0.368 \text{ M}_\odot \cdot \text{yr}^{-1}$ (Kolokythas et al., 2022). We measure extraordinarily young stellar populations for NGC 7252’s inner and outer region, with χ_ν^2 -weighted ages of $0.6 \pm 0.2 \text{ Gyr}$ and $2.7 \pm 1.3 \text{ Gyr}$, respectively. In particular, we obtain excellent FIREFLY fits for NGC 7252’s inner spectrum, with $\chi_\nu^2 \sim 1$ using MILES and STELIB.

NGC 7377: NGC 7377 is classified as an intermediate disc galaxy, according to the scheme of Jarrett et al. (2019) (Kolokythas et al., 2022). Such galaxies are passively evolving systems with semi-quiscent star-formation within their structure (Jarrett et al., 2019; Kolokythas et al., 2022). For NGC 7377, we detect stellar populations of intermediate age, which is reasonable for an intermediate disc galaxy such as NGC 7377.

4.2 The MHONGOOSE Galaxy J1153

As discussed in sections 1.5.2, 3.3 and 3.4, we measured the spatially-resolved stellar kinematics and stellar populations of J1153 using the same techniques used for the CLoGS BGEs.

Spatially-resolved stellar kinematics: As evident from Figure 3.15, we observe a strong stellar rotation of $\sim 87.5 \text{ km.s}^{-1}$ for J1153 across its major axis. We further observe a positive stellar velocity dispersion slope of $\eta \approx 0.17$, as shown in Figure 3.14. In theory, the stellar kinematics of J1153 can be compared with its gas kinematics, which are not necessarily aligned. Such an exercise could reveal the origin of the galaxy’s cold gas, such as its HI-content. By understanding the origin and nature of the galaxy’s HI, its star-formation processes can be better understood. We encourage further spectroscopic studies of J1153 to investigate its cold gas content.

Stellar populations: We measure a radially decreasing stellar population age for J1153 across its minor- and major axes, as shown in Figures 3.16 and 3.17. In more detail, we report a χ^2_ν -weighted age of ~ 3 Gyr for J1153’s central region, which decreases to a χ^2_ν -weighted age of ~ 0.5 Gyr 3 kpc away from the galaxy’s centre. The FIREFLY fits that use the MILES stellar library are the most statistically significant, with $\chi^2_\nu \sim 0.8$ at J1153’s centre, and with $\chi^2_\nu \sim 1.1$ at the outskirts of J1153. The negative stellar population age gradient can potentially be attributed to the galaxy’s radially decreasing concentration of HI (Sardone et al., 2021b). However, further complementary optical and radio studies of J1153 are required to better understand the star-formation history and stellar populations of J1153. These studies will, in principle, allow us to understand how HI is processed within J1153 (and other MHONGOOSE galaxies), and in what manner star-formation is repressed or triggered within these HI-dense regions.

Chapter 5

Concluding Remarks and Future Work

“Though here at journey’s end I lie in darkness buried deep.
Beyond all towers strong and high. Beyond all mountains steep.
Above all shadows rides the sun and stars for ever dwell: I will
not say the day is done, nor bid the stars farewell.”

J.R.R Tolkien

In this study, spatially-resolved optical spectra were obtained for our sub-sample of 18 CLoGS BGEs, as discussed in section 2.1, using the SALT RSS. Similarly, spatially-resolved optical spectra were obtained for the MHONGOOSE galaxy J1153, as discussed in section 2.2. The data reduction process is discussed in detail in Chapter 2, with the supporting written code listed in Appendix B. These spectra were fitted using full-spectrum fitting software to derive the properties of these galaxies. In more detail, pPXF was used to measure the spatially-resolved stellar kinematics of these galaxies, as discussed in section 2.5; and FIREFLY was used to measure their stellar population properties, as discussed in section 2.6. These results are presented throughout Chapter 3, and Appendices E to G. In Chapter 4, the spatially-resolved stellar kinematics and stellar populations of the CLoGS BGEs and the MHONGOOSE galaxy J1153 were discussed. In this chapter, the most significant results are summarised.

5.1 CLoGS BGEs

Similar to Loubser et al. (2018), who studied the stellar kinematics of 23 CLoGS BGEs using the Hobby-Eberly Telescope, we studied the stellar kinematics of 18 CLoGS BGEs using the Southern African Large Telescope.

Spatially-resolved stellar kinematics: It was found that some of the CLoGS BGEs show a marginal degree of stellar rotation. These BGEs included NGC 128, NGC 4697, NGC 5084 and NGC 5153, all of which had an anisotropy parameter of $V_{max}/\sigma_0 \gtrsim 0.75$. Although some of the CLoGS BGEs showed marginal rotation, all of the CLoGS BGEs studied here can be regarded as pressure supported systems and not rotationally supported systems within reasonable error. This is line with Loubser et al. (2018). We similarly measure a variety of different stellar kinematics, which we compared to complementary data from the latest galaxy surveys and galaxy evolution simulations.

With regard to other galaxy surveys, it was found that the stellar kinematics of the CLoGS BGEs more closely resemble field ETGs than BCGs. In more detail, the CLoGS BGEs show velocity dispersion slopes similar to the ETG samples of Cappellari et al. (2006) and Mehlert et al. (2000) in the central velocity dispersion range $2.1 \leq \log(\sigma_0) \leq 2.4$. With regard to the latest galaxy evolution simulations, it is unclear whether these simulations can accurately model the range of stellar kinematics we observe for the CLoGS BGEs. For instance, the Romulus BGGs of Jung et al. (2022), and the DIANOGA BCGs of Marini et al. (2021), do not show the same diversity of velocity dispersion slopes as the CLoGS BGEs. In more detail, the Romulus BGGs, with velocity dispersion slopes $-0.3 \leq \eta \leq 0.1$, and the DIANOGA BCGs, with velocity dispersion slopes $-0.1 \leq \eta \leq 0.3$, do not reflect the velocity dispersion slopes of the CLoGS BGEs, which fall in the range $-0.1 \leq \eta \leq 0.1$. This implies that our current galaxy evolution models could be improved to more accurately reflect the dark matter content, baryonic processes and hydrodynamic processes present within group environments. We openly invite and encourage those building these models to make use of the new observational data for the CLoGS BGEs, as presented in this thesis.

Stellar populations: In agreement with recent studies, such as Bildfell et al. (2008), Loubser et al. (2016) and Oppenheimer et al. (2021), we confirm that young stellar populations are present in some brightest group early-type galaxies. From our sub-sample of 18 CLoGS BGEs, young stellar populations were found for ESO 507-25, NGC 128 and NGC 7252 with a high degree of certainty, and with favourable χ^2_ν statistics across the different FIREFLY fits. The young stellar populations of these galaxies can be linked to their notable supply of cold gas, and their high star formation rates (O’Sullivan et al., 2015; O’Sullivan et al., 2018a; Kolokythas et al., 2022). NGC 7252 hosts the largest number of young stars, with an inner stellar population age of ~ 0.6 Gyr, which contribute to most ($> 95\%$) of the light we observe from the galaxy. In contrast, the stellar populations of ESO 507-25 and NGC 128 are only partly young. Based on our FIREFLY fits, 50% of the light from ESO 507-25’s inner region comes from a stellar population with an age of ~ 1.5 Gyr. Similarly, 30% of the light from NGC 128’s inner region comes from a stellar population with an age of ~ 2 Gyr. These estimates are based on the light-weighted stellar population ages measured for ESO 507-25 and NGC 128 with the best χ^2_ν statistics; i.e.

the FIREFLY fit for ESO 507-25 using the ELODIE stellar library, and the FIREFLY fit for NGC 128 using the STELIB stellar library.

We further measure possible evidence of AGN-feedback within group environments. In particular, very old stellar populations were measured for NGC 193 and NGC 1550, both of which are known to have large-scale radio jets (Kolokythas et al., 2018; Kolokythas et al., 2020). An old stellar population of ~ 12 Gyr was measured for NGC 1550’s outer region, with high certainty when using the ELODIE stellar library. We suggest that NGC 1550’s AGN activity suppressed star formation in the outer regions of the galaxy. The same is plausible for NGC 193; however, less certain than the case of NGC 1550. Old stellar populations were also measured for NGC 5044, which is known to have a remnant radio-jet and thought to be at the start of a new AGN-feedback cycle.

As discussed in section 1.4.2, the stellar population properties derived with stellar population synthesis strongly depend on the stellar library used. We wish to remind the reader that the stellar population properties presented in this study has been subject to the stellar libraries used and their limitations. Future work may involve a more in depth study as to how the different stellar libraries impact the derived stellar population properties. The use of other stellar libraries may potentially reveal additional stellar population properties not presented in this study.

Future work would further involve a similar optical spectroscopic study of the remaining sample of the CLoGS BGEs; namely: NGC 252, NGC 1106, NGC 1167, NGC 1407, NGC 4956, NGC 5322, and NGC 5444.

5.2 The MHONGOOSE Galaxy J1153

We have demonstrated with our study of J1153 that optical spectroscopy with the SALT RSS can feasibly obtain spatially resolved stellar kinematics and stellar population properties for the MHONGOOSE sample of galaxies. Through the combination of various spectroscopic images of similar resolution and axis orientation, a sufficient signal-to-noise ratio can be obtained to reveal the stellar kinematics and stellar population properties of a faint galaxy such as J1153.

A strong stellar rotation of $\sim 87.5 \text{ km.s}^{-1}$ and a positive velocity dispersion slope of $\eta \approx 0.17$ were observed for J1153 across its major axis. A complementary study of J1153’s gas kinematics is being conducted with MeerKAT, as part of the ongoing MHONGOOSE survey. We suggest combining and studying the MeerKAT and SALT results together when the MHONGOOSE observations are completed.

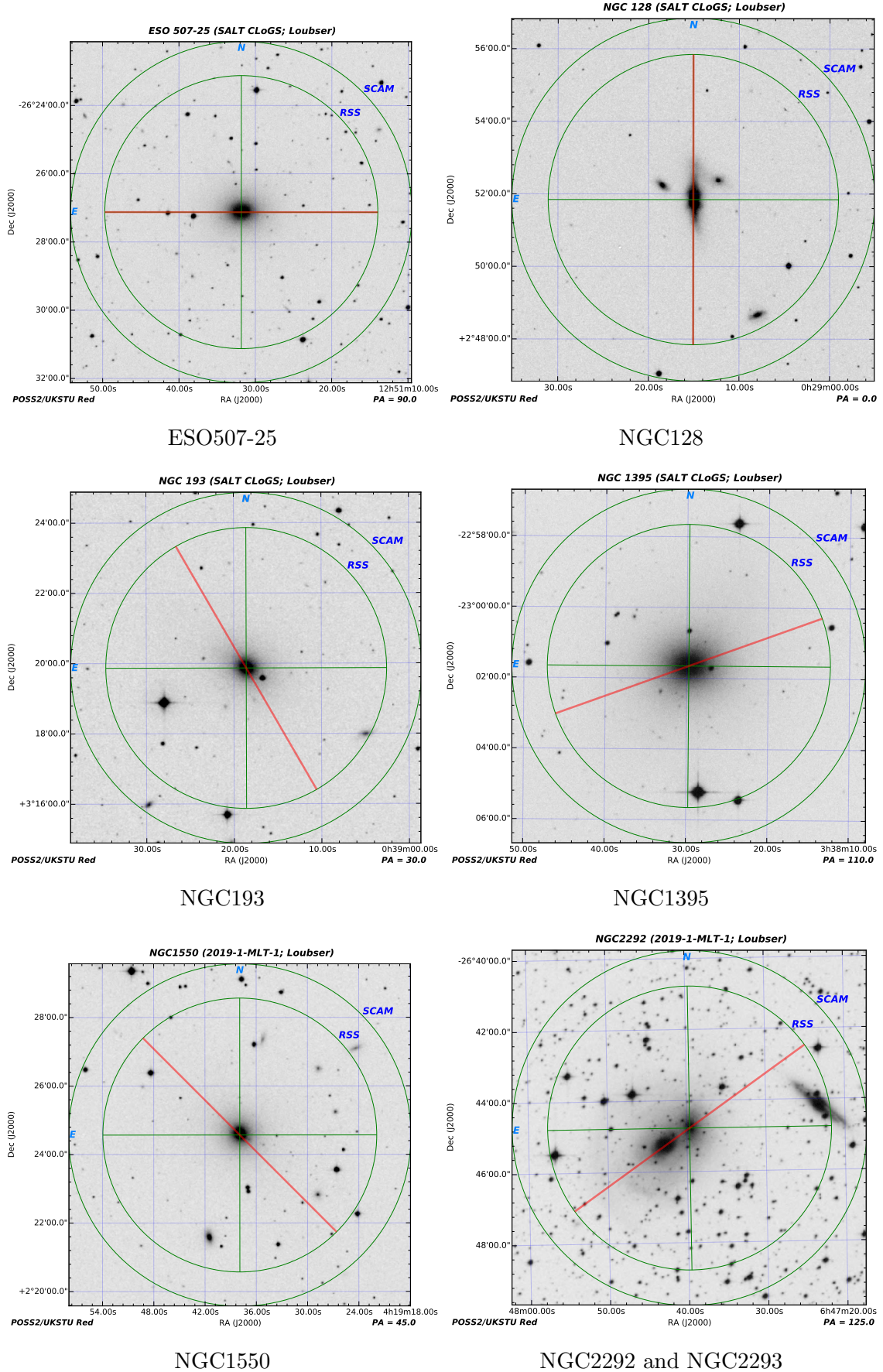
A negative stellar population age gradient is observed for J1153, which may be linked to the galaxy's radially decreasing supply of HI (Sardone et al., 2021b). We encourage further complementary stellar population studies of J1153 to understand how its star-formation history and stellar populations may be linked to its HI-content.

Future work would involve an optical spectroscopic study of the remaining MHONGOOSE sample of galaxies, including, but not limited to HIPASS J0351-28, HIPASS J0459-26 and HIPASS J1303-17b.

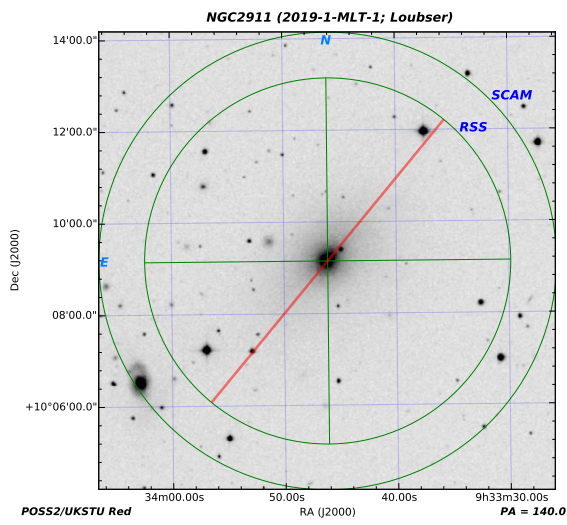
Appendix A

Finding Charts for the SALT RSS Spectroscopic Observations

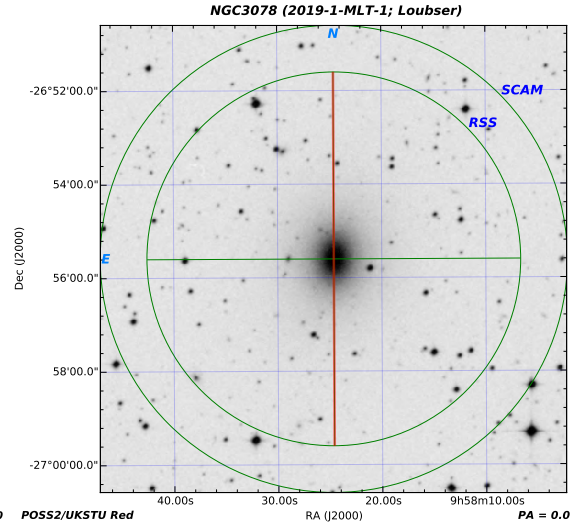
A.1 CLoGS BGEs



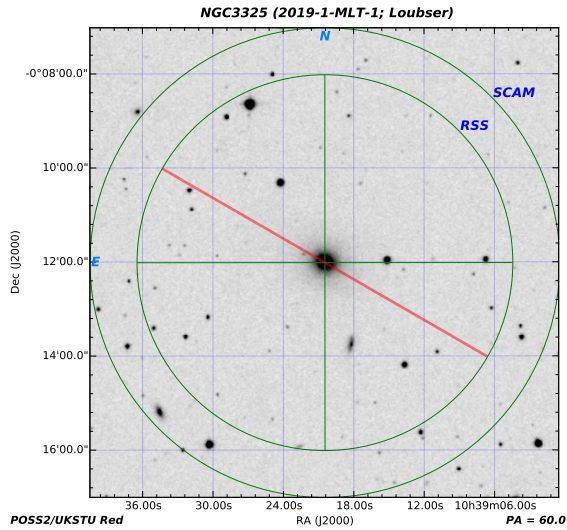
APPENDIX A. FINDING CHARTS FOR THE SALT RSS SPECTROSCOPIC OBSERVATIONS⁹⁵



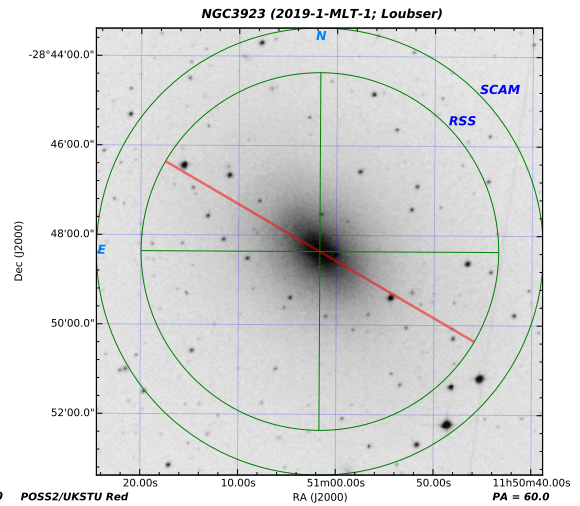
NGC2911



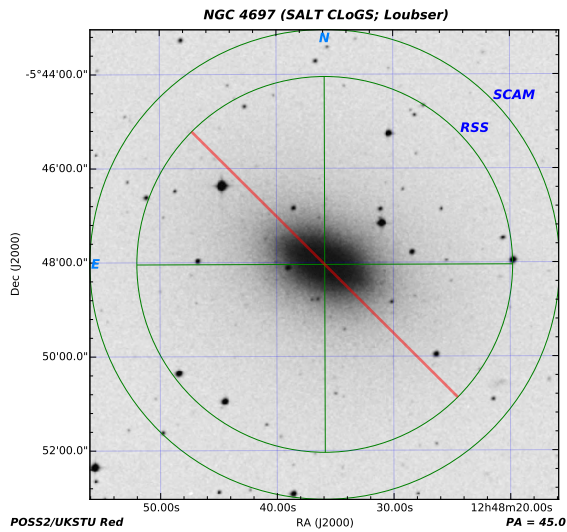
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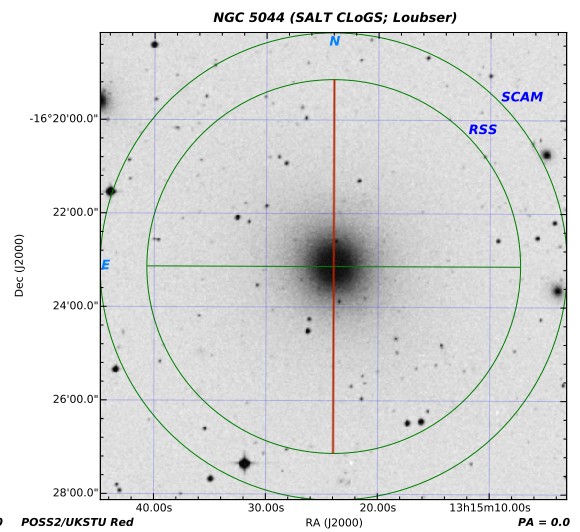
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NGC3923

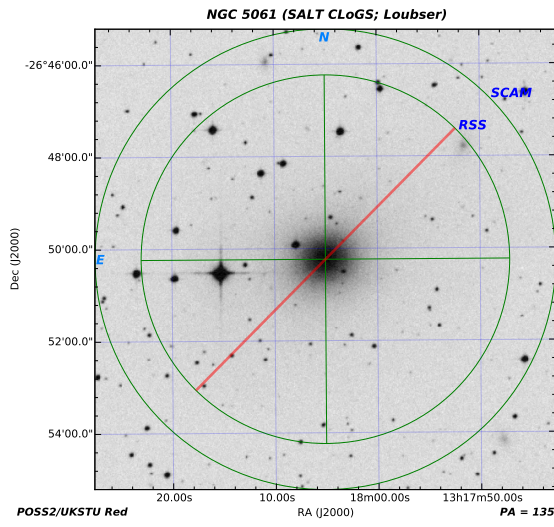


NGC4697

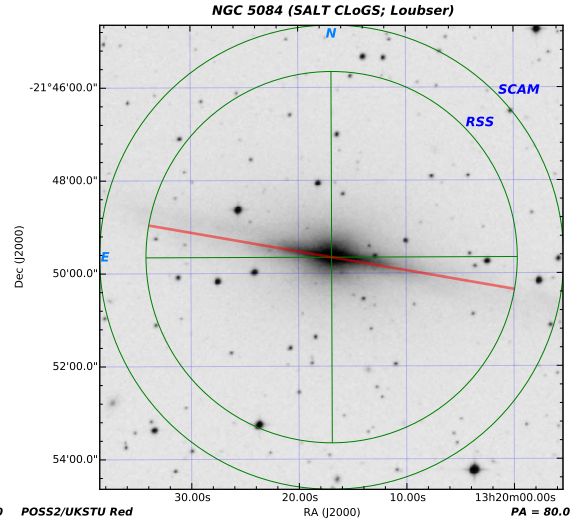


NGC5044

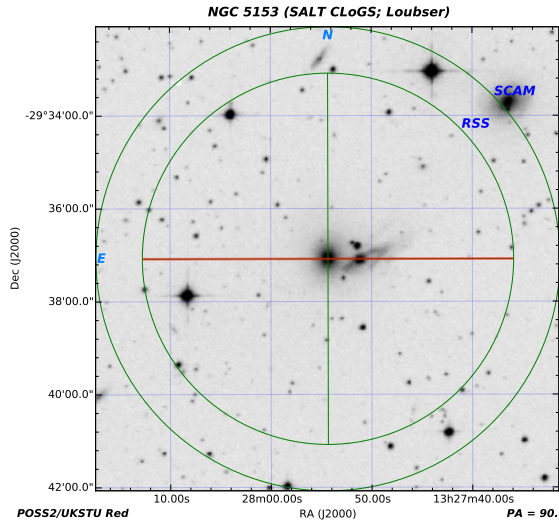
APPENDIX A. FINDING CHARTS FOR THE SALT RSS SPECTROSCOPIC OBSERVATIONS⁹⁶



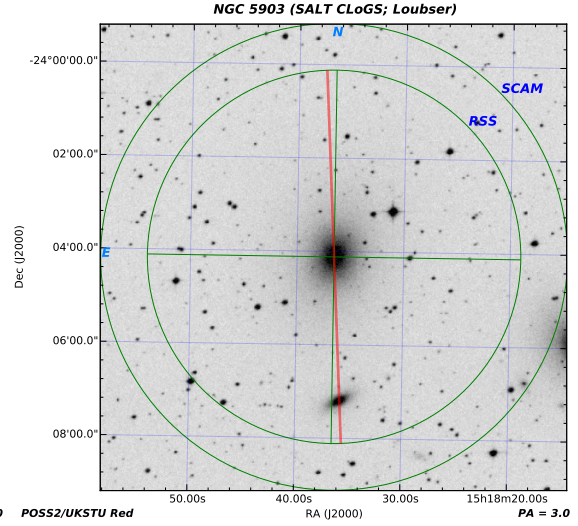
NGC5061



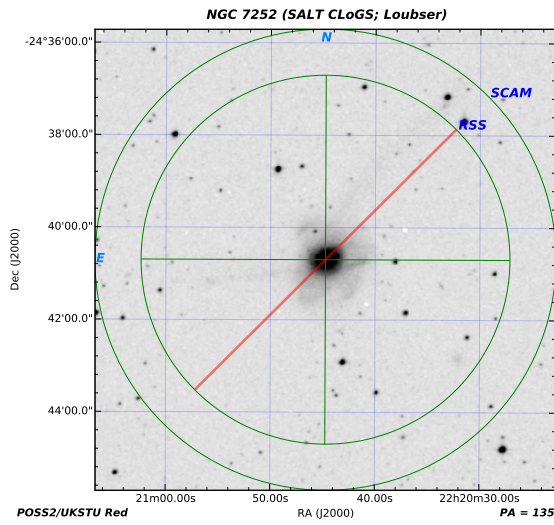
NGC5084



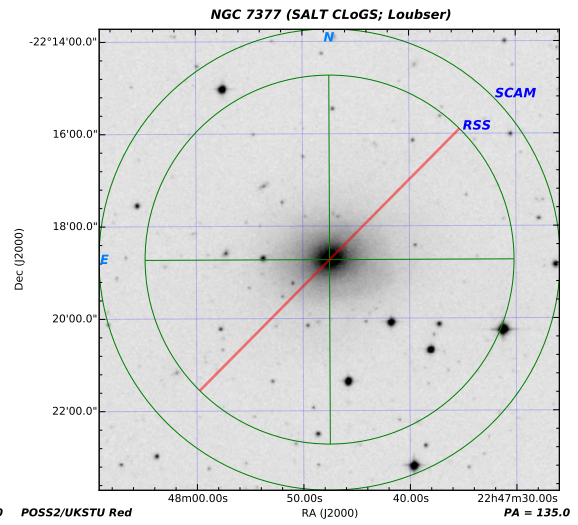
NGC5153 and NGC5152



NGC5903

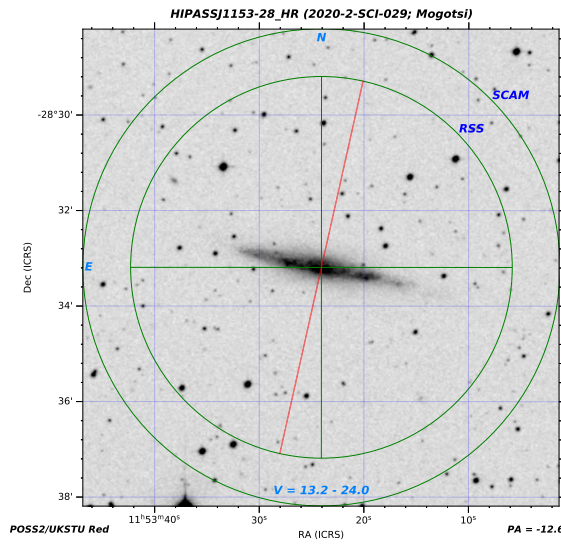


NGC7252

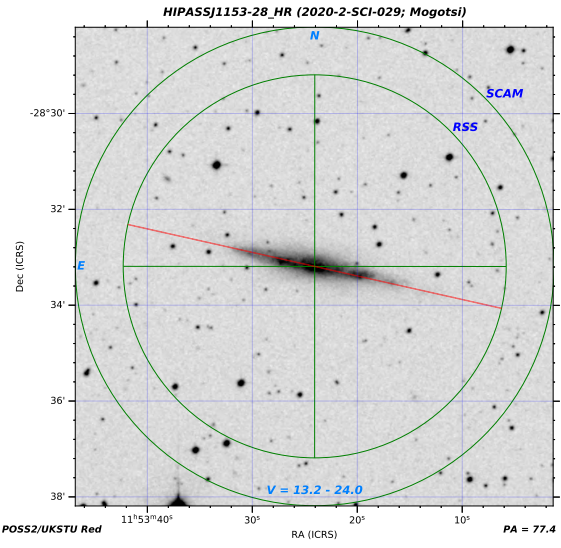


NGC7377

A.2 MHONGOOSE Galaxy J1153



HIPASS J1153-28 (Minor Axis)



HIPASS J1153-28 (Major Axis)

Supporting Python Code for the SALT RSS Pipeline

```

1 '''
2 ++++++
3
4 SALT RSS Sensitivity File Creator
5
6 This program creates a sensitivity file for a given standard star that has
7     been
8 reduced by the SALT RSS pipeline.
9
10 The target FITS file is typically a 2D flux spectrum of the standard star.
11
12 The SALT RSS Data Reduction procedure is described in:
13 http://mips.as.arizona.edu/~khainline/salt\_redux.html
14 ++++++
15 '''
16
17 '''
18 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
19 Import Libraries
20 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
21 '''
22
23 import os # For bash commands
24 from pyraf import iraf # For IRAF commands in Python
25 import astropy.io.fits as fits # For FITS file handling
26
27 '''

```



```

118 # Change filepath
119 os.chdir(path)
120
121 # Get name of star
122 star = raw_input('\nEnter file name (with extension) of the standard star
      FITS file: ')
123
124 # Create Standard File
125 standard = standard(star)
126
127 # Create Sens File
128 sensitivity(star, standard)

```

B.2 Flux Calibration Script

[illegible]


```

17 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
18 '''
19 z_ES0507 = 0.01079
20 z_NGC128 = 0.012981
21 z_NGC193 = 0.01472
22 z_NGC1395 = 0.00573
23 z_NGC1550 = 0.01239
24 z_NGC2292 = 0.00679
25 z_NGC2293 = 0.00679
26 z_NGC2911 = 0.01062
27 z_NGC3078 = 0.00861
28 z_NGC3325 = 0.01887
29 z_NGC3923 = 0.00580
30 z_NGC4697 = 0.00414
31 z_NGC5044 = 0.00928
32 z_NGC5061 = 0.00694
33 z_NGC5084 = 0.00574
34 z_NGC5152 = 0.01390
35 z_NGC5153 = 0.01441
36 z_NGC5903 = 0.00856
37 z_NGC7252 = 0.01598
38 z_NGC7377 = 0.01114
39
40 '''
41 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
42 Load IRAF Libraries
43 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
44 '''
45
46 iraf.images()
47 iraf.images.imutil()
48
49
50 def FITS_to_txt(spec, err_spec, name):
51     global path
52     os.chdir(path)
53
54     hdu1 = fits.open(spec)
55     hdr1 = hdu1[0].header
56     flux = hdu1[0].data
57     flux = np.array(flux, dtype=np.float64)
58
59     start_wave = hdr1['CRVAL1'] # Initial wavelength
60     step = hdr1['CDELTA1'] # Increment per pixel
61
62     w0, dw, n = start_wave, step, len(flux)
63     w = start_wave + step * n
64     wave = np.linspace(w0, w, n, endpoint=False)
65
66     hdu2 = fits.open(err_spec)
67     hdr2 = hdu2[0].header

```

```

68     error = hdu2[0].data
69     error = np.array(error, dtype=np.float64)
70
71     txt_file = '{}.txt'.format(name)
72
73     with open(txt_file, 'w') as f:
74         for a, b, c in zip(wave, flux, error):
75             f.write('{} {} {} \n'.format(a, b, c))
76     print('-----')
77     print('FITS to .txt: DONE')
78
79     return txt_file
80
81
82 def extract(file, aperture, kpc):
83     global z
84     global path
85
86     basename = Path(file).stem
87
88     input = []
89     for line in aperture:
90         input = np.append(input, '{}[*,{}] \n'.format(file, int(line)))
91
92     with open('aperture.txt', 'w') as f:
93         for item in input:
94             print '>> f, item'
95
96     output = '{}_{}_kpc.fits'.format(basename, kpc)
97     iraf.images.imutil.imsum(input="@aperture.txt", output=output, verbose=
'No', mode='al')
98     iraf.imutil.hedit(images=output, fields='REDSHIFT', value=z, update='
Yes')
99
100     os.remove('aperture.txt')
101
102     return output
103
104
105 if __name__ == '__main__':
106
107
108     '''
109     In this case NGC 2293 is used as an example.
110     However the code can be changed to use any CLoGS BGE.
111     '''
112
113     # Set Path
114     path = '/home/user/Desktop/NGC2293/final/'
115     os.chdir(path)
116     # Set File

```



```

168         aperture = np.arange(pix_start[0], pix_start[1], 1)
169         kpc = -0.5
170         spec = extract(file, aperture, kpc)
171     except:
172         print('File already exists')
173
174     try:
175         kpc_start = np.array([0, 1])
176         pix_start = centre + (pix_per_kpc * kpc_start)
177         pix_start = np.array(pix_start, dtype=int)
178         aperture = np.arange(pix_start[0], pix_start[1], 1)
179         kpc = 0.5
180         spec = extract(file, aperture, kpc)
181     except:
182         print('File already exists')
183
184     if mode == 'FIREFLY':
185
186         basename = Path(file).stem
187
188         kpc_start = []
189         kpc_start = np.append(kpc_start, -1.0)
190         kpc_start = np.append(kpc_start, -0.25)
191         kpc_start = np.append(kpc_start, 0)
192         kpc_start = np.append(kpc_start, 0.25)
193         kpc_start = np.append(kpc_start, 1)
194
195         kpc_start = kpc_start * Re
196
197         print('kpc_start = {}'.format(kpc_start))
198
199         pix_start = centre + (pix_per_kpc * kpc_start)
200         pix_start = np.array(pix_start, dtype=int)
201         print(pix_start)
202
203         for i in range(1, len(pix_start)):
204             aperture = np.arange(pix_start[i - 1], pix_start[i], 1)
205             if aperture.size >= 1:
206                 kpc = (((kpc_start[i - 1] + kpc_start[i]) / 2.0))
207                 kpc = np.round(kpc, 2)
208                 print(aperture)
209                 print(kpc)
210                 spec = extract(file, aperture, kpc)
211                 err_spec = extract(err_file, aperture, kpc)
212
213         files = os.listdir('.')
214         for f in files:
215             kpc = re.findall('-?\d+\\.\\d+', f)
216             print(kpc)
217             if kpc == []:
218                 files.remove(f)

```

```

219         print('{} removed.'.format(f))
220     if file in files:
221         files.remove(file)
222     if err_file in files:
223         files.remove(err_file)
224     print('Files = {}'.format(files))
225
226     kpcs = []
227     for f in files:
228         kpc = re.findall('-?\d+\\.\\d+', f)
229         kpcs = np.append(kpcs, kpc)
230     print('kpcs = {}'.format(kpcs))
231
232     kpcs = np.array(kpcs, dtype=float)
233     '''
234     >>>>>>>>>>>>>>>>>>>>>>>>>>>>
235     Sum Inner Region
236     >>>>>>>>>>>>>>>>>>>>>>>>>>>>
237     '''
238
239     min_kpc = np.min(np.abs(kpcs))
240
241     inner_left_kpc = -min_kpc
242     inner_right_kpc = min_kpc
243
244     for f in files:
245         kpc = re.findall('-?\d+\\.\\d+', f)
246         kpc = np.float64(kpc)
247         if kpc == inner_left_kpc and 'err' not in f:
248             inner_left_file = f
249         if kpc == inner_right_kpc and 'err' not in f:
250             inner_right_file = f
251         if kpc == inner_left_kpc and 'err' in f:
252             err_inner_left_file = f
253         if kpc == inner_right_kpc and 'err' in f:
254             err_inner_right_file = f
255
256     print(inner_left_file)
257     print(inner_right_file)
258     inner_file = '{}_Inner.fits'.format(basename)
259     print(err_inner_left_file)
260     print(err_inner_right_file)
261     err_inner_file = 'err-{}_Inner.fits'.format(basename)
262
263     iraf.images.imutil.imsum(input="{},{}".format(inner_left_file,
inner_right_file), output=inner_file,
                                verbose='No', mode='al')
264     iraf.imutil.hedit(images=inner_file, fields='REDSHIFT', value=z,
update='Yes')
265
266
267     iraf.images.imutil.imsum(input="{},{}".format(err_inner_left_file,
```

```

err_inner_right_file), output=err_inner_file,
    verbose='No', mode='al')
    iraf.imutil.hedit(images=err_inner_file, fields='REDSHIFT', value=z
, update='Yes')

FITS_to_txt(inner_file, err_inner_file, '{}_Inner'.format(basename)
)

'''
>>>>>>>>>>>>>>>>>>>>>>>>>
Sum Outer Region
>>>>>>>>>>>>>>>>>>>>>>>>>
'''

max_kpc = np.max(np.abs(kpcs))

outer_left_kpc = -max_kpc
outer_right_kpc = max_kpc

for f in files:
    kpc = re.findall('-?\d+\.\d+', f)
    kpc = np.float64(kpc)
    if kpc == outer_left_kpc and 'err' not in f:
        outer_left_file = f
    if kpc == outer_right_kpc and 'err' not in f:
        outer_right_file = f
    if kpc == outer_left_kpc and 'err' in f:
        err_outer_left_file = f
    if kpc == outer_right_kpc and 'err' in f:
        err_outer_right_file = f

print(outer_left_file)
print(outer_right_file)
outer_file = '{}_Outer.fits'.format(basename)
print(err_outer_left_file)
print(err_outer_right_file)
err_outer_file = 'err-{}_Outer.fits'.format(basename)

    iraf.images.imutil.imsum(input="{},{}".format(outer_left_file,
outer_right_file), output=outer_file,
    verbose='No', mode='al')
    iraf.imutil.hedit(images=outer_file, fields='REDSHIFT', value=z,
update='Yes')

    iraf.images.imutil.imsum(input="{},{}".format(err_outer_left_file,
err_outer_right_file), output=err_outer_file,
    verbose='No', mode='al')
    iraf.imutil.hedit(images=err_outer_file, fields='REDSHIFT', value=z
, update='Yes')

FITS_to_txt(outer_file, err_outer_file, '{}_Outer'.format(basename)

```

```

312     if mode == 'TXT':
313
314         basename = Path(file).stem
315
316         inner_file = '{}_Inner.fits'.format(basename)
317         err_inner_file = 'err-{}_Inner.fits'.format(basename)
318         outer_file = '{}_Outer.fits'.format(basename)
319         err_outer_file = 'err-{}_Outer.fits'.format(basename)
320
321         FITS_to_txt(inner_file, err_inner_file, '{}_Inner'.format(basename)
322 )
323         FITS_to_txt(outer_file, err_outer_file, '{}_Outer'.format(basename)
324 )
325
326     if mode == 'FIREFLY_MHONGGOOSE':
327         kpc_start = []
328         kpc_start = np.append(kpc_start, -1)
329         kpc_start = np.append(kpc_start, -0.25)
330         kpc_start = np.append(kpc_start, 0.25)
331         kpc_start = np.append(kpc_start, 1)
332
333         print('kpc_start = {}'.format(kpc_start))
334
335         pix_start = centre + (pix_per_kpc * kpc_start)
336         pix_start = np.array(pix_start, dtype=int)
337         print(pix_start)
338
339         for i in range(1, len(pix_start)):
340             aperture = np.arange(pix_start[i - 1], pix_start[i], 1)
341             if aperture.size >= 1:
342                 kpc = (((kpc_start[i - 1] + kpc_start[i]) / 2.0))
343                 kpc = np.round(kpc, 2)
344                 print(aperture)
345                 print(kpc)
346                 spec = extract(file, aperture, kpc)

```

B.4 Aperture Extraction for the MHONGOOSE Galaxy J1153

```
1 '''
2 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
3 Import Libraries
4 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
5 '''
6
7 import os # For bash commands
8 import numpy as np # For array handling
9 from pyraf import iraf # For IRAF commands
```

```

10 import astropy.io.fits as fits # For FITS file handling
11 from pathlib import Path      # To extract filenames
12 import glob
13 import re
14
15 '''
16 >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
17 Load IRAF Libraries
18 >>>>>>>>>>>>>>>>>>>>>>>>>
19 '''
20
21 iraf.images()
22 iraf.images.imutil()
23
24
25 def FITS_to_txt(spec, err_spec, name):
26
27     global path
28     os.chdir(path)
29
30     hdu1 = fits.open(spec)
31     hdr1 = hdu1[0].header
32     flux = hdu1[0].data
33     flux = np.array(flux, dtype=np.float64)
34
35     start_wave = hdr1['CRVAL1'] # Initial wavelengthh
36     step = hdr1['CDELTA1']    # Increment per pixel
37
38     w0, dw, n = start_wave, step, len(flux)
39     w = start_wave + step * n
40     wave = np.linspace(w0, w, n, endpoint=False)
41
42     hdu2 = fits.open(err_spec)
43     hdr2 = hdu2[0].header
44     error = hdu2[0].data
45     error = np.array(error, dtype=np.float64)
46
47     txt_file = '{}.txt'.format(name)
48
49     with open(txt_file, 'w') as f:
50         for a, b, c in zip(wave, flux, error):
51             f.write('{} {} {}\n'.format(a, b, c))
52     print('-----')
53     print('FITS to .txt: DONE')
54
55     return txt_file
56
57
58 def speclist(txt_file1, txt_file2, kpc):
59
60     global path

```



```

160     kpc_start = np.append(kpc_start, np.linspace(-0.25, 0.25, 21))[:-1]
161     kpc_start = np.append(kpc_start, np.linspace(0.25, 0.5, 9))[:-1]
162     kpc_start = np.append(kpc_start, np.linspace(0.5, 0.75, 6))[:-1]
163     kpc_start = np.append(kpc_start, np.linspace(0.75, 1, 3))
164     kpc_start = np.append(kpc_start, 1.25)
165
166     kpc_start = kpc_start * D
167
168     print('kpc_start = {}'.format(kpc_start))
169
170     pix_start1 = centre1 + (pix_per_kpc * kpc_start)
171     pix_start1 = np.array(pix_start1, dtype=int)
172
173     pix_start2 = centre2 + (pix_per_kpc * kpc_start)
174     pix_start2 = np.array(pix_start2, dtype=int)
175
176     print(pix_start1)
177     print(pix_start2)
178
179     for i in range(1, len(pix_start1)):
180         aperture1 = np.arange(pix_start1[i - 1], pix_start1[i], 1)
181         aperture2 = np.arange(pix_start2[i - 1], pix_start2[i], 1)
182         if (aperture1.size >= 1) and (aperture2.size >= 1):
183             kpc = (((kpc_start[i - 1] + kpc_start[i]) / 2.0))
184             kpc = np.round(kpc, 2)
185             spec1, spec2 = extract_multi(file1, file2, aperture1,
aperture2, kpc)
186             err_spec1, err_spec2 = extract_multi(err_file1, err_file2,
aperture1, aperture2, kpc)
187             txt_file1 = FITS_to_txt(spec1, err_spec1, Path(spec1).stem)
188             txt_file2 = FITS_to_txt(spec2, err_spec2, Path(spec2).stem)
189             speclist(txt_file1, txt_file2, kpc)
190
191     if mode == 'FIREFLY_MAJOR':
192         kpc_start = []
193         kpc_start = np.append(kpc_start, -4)
194         kpc_start = np.append(kpc_start, -1.5)
195         kpc_start = np.append(kpc_start, -0.25)
196         kpc_start = np.append(kpc_start, 0.25)
197         kpc_start = np.append(kpc_start, 1.5)
198         kpc_start = np.append(kpc_start, 4)
199
200     print('kpc_start = {}'.format(kpc_start))
201
202     pix_start1 = centre1 + (pix_per_kpc * kpc_start)
203     pix_start1 = np.array(pix_start1, dtype=int)
204
205     pix_start2 = centre2 + (pix_per_kpc * kpc_start)
206     pix_start2 = np.array(pix_start2, dtype=int)
207
208     print(pix_start1)

```

```

209     print(pix_start2)
210
211     for i in range(1, len(pix_start1)):
212         aperture1 = np.arange(pix_start1[i - 1], pix_start1[i], 1)
213         aperture2 = np.arange(pix_start2[i - 1], pix_start2[i], 1)
214         if (aperture1.size >= 1) and (aperture2.size >= 1):
215             kpc = (((kpc_start[i - 1] + kpc_start[i]) / 2.0))
216             kpc = np.round(kpc, 2)
217             spec1, spec2 = extract_multi(file1, file2, aperture1,
aperture2, kpc)
218             err_spec1, err_spec2 = extract_multi(err_file1, err_file2,
aperture1, aperture2, kpc)
219             txt_file1 = FITS_to_txt(spec1, err_spec1, Path(spec1).stem)
220             txt_file2 = FITS_to_txt(spec2, err_spec2, Path(spec2).stem)
221             speclist(txt_file1, txt_file2, kpc)
222
223     if mode == 'FIREFLY_MINOR':
224         kpc_start = []
225         kpc_start = np.append(kpc_start, -1)
226         kpc_start = np.append(kpc_start, -0.25)
227         kpc_start = np.append(kpc_start, 0.25)
228         kpc_start = np.append(kpc_start, 1)
229
230     print('kpc_start = {}'.format(kpc_start))
231
232     pix_start1 = centre1 + (pix_per_kpc * kpc_start)
233     pix_start1 = np.array(pix_start1, dtype=int)
234
235     pix_start2 = centre2 + (pix_per_kpc * kpc_start)
236     pix_start2 = np.array(pix_start2, dtype=int)
237
238     print(pix_start1)
239     print(pix_start2)
240
241     for i in range(1, len(pix_start1)):
242         aperture1 = np.arange(pix_start1[i - 1], pix_start1[i], 1)
243         aperture2 = np.arange(pix_start2[i - 1], pix_start2[i], 1)
244         if (aperture1.size >= 1) and (aperture2.size >= 1):
245             kpc = (((kpc_start[i - 1] + kpc_start[i]) / 2.0))
246             kpc = np.round(kpc, 2)
247             spec1, spec2 = extract_multi(file1, file2, aperture1,
aperture2, kpc)
248             err_spec1, err_spec2 = extract_multi(err_file1, err_file2,
aperture1, aperture2, kpc)
249             txt_file1 = FITS_to_txt(spec1, err_spec1, Path(spec1).stem)
250             txt_file2 = FITS_to_txt(spec2, err_spec2, Path(spec2).stem)
251             speclist(txt_file1, txt_file2, kpc)

```

B.5 SALT RSS Image Convolution Script

[illegible]


```

97     '''
98
99     Calculates the instrumental FWHM resolution of the telescope (in this
100     case the Southern African Large Telescope),
101     given the ARC FITS file. The FWHM is calculated based off the 4333
102     Angstrom line. This code will only work if the given
103     ARC file includes the 4333 Angstrom emission line.
104
105     :param ARC [String]: File name of ARC FITS file to be opened.
106     :param centre [Float]: Number of the central pixel of the astronomical
107     source on the FITS image.
108
109     :return: FWHM [float]: Instrumental resolution of the telescope.
110     :return: FWHM [float]: Error of the instrumental resolution of the
111     telescope.
112
113     '''
114
115     # Read FITS file
116     wave, flux = read_FITS(ARC, centre)
117
118     # Set wavelength range for fitting the Gaussian.
119     # In this case we fit the 4333 Angstrom emission line.
120     line_4333 = [(wave >= 4320) & (wave <= 4340)]
121     flux = flux[tuple(line_4333)]
122     wave = wave[tuple(line_4333)]
123
124     # Determine which data points have a signal above 5 sigma.
125     n = len(flux)
126     noise = 0.6052697 * np.median(np.abs(2.0 * flux[2:n - 2] - flux[0:n -
127     4] - flux[4:n]))
128     flux_base = flux[flux < 5 * noise]
129     wave_base = wave[flux < 5 * noise]
130
131     # Fit the baseline (all data points with a signal less than 5 sigma are
132     # considered to be the baseline).
133     def straight_line(x, m, c):
134         return m * x + c
135     coeff, var_matrix = curve_fit(straight_line, wave_base, flux_base)
136     m = coeff[0]
137     c = coeff[1]
138     baseline = m * wave + c
139
140     # Subtract the baseline
141     smooth_flux = flux - baseline
142
143     # Fit the Gaussian
144     def Gauss(x, a, mu, sigma):
145         return a * np.exp(-(x - mu) ** 2 / (2 * sigma ** 2))
146     amp = np.max(smooth_flux)
147     mean = np.mean(wave)

```


[illegible]

```
231 src2 = raw_input('\nEnter file path & name of the second GALAXY FITS file (  
    with full path and extension):  ')  
232  
233 # Get 2nd ARC File  
234 ARC2 = raw_input('\nEnter file path & name of the second ARC FITS file (  
    with full path and extension):  ')  
235  
236 # Get 2nd File centre pixel  
237 ctr2 = raw_input('\nEnter the centre pixel of the second galaxy:  ')  
238  
239 # Convolve Files  
240 convolve(work_dir, src1, ARC1, ctr1, src2, ARC2, ctr2)
```

Appendix C

Identification Screens Used throughout the SALT RSS Pipeline

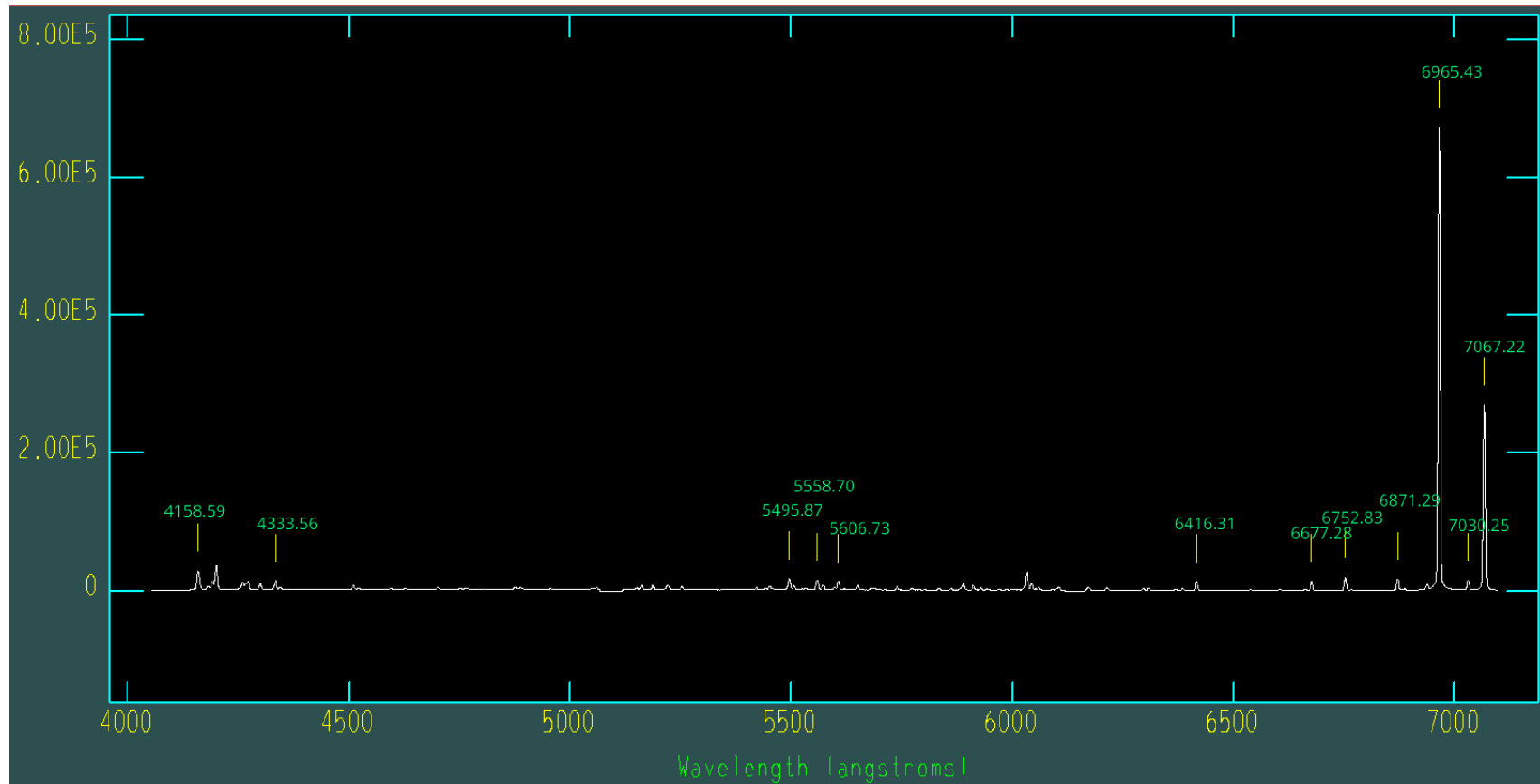


Figure C.1: Identification screen for the Argon (Ar) ARC lamp for PG0900 SALT RSS data. The spectral lines that were identified are indicated with the yellow lines and their corresponding wavelength in Angstrom is shown in green.

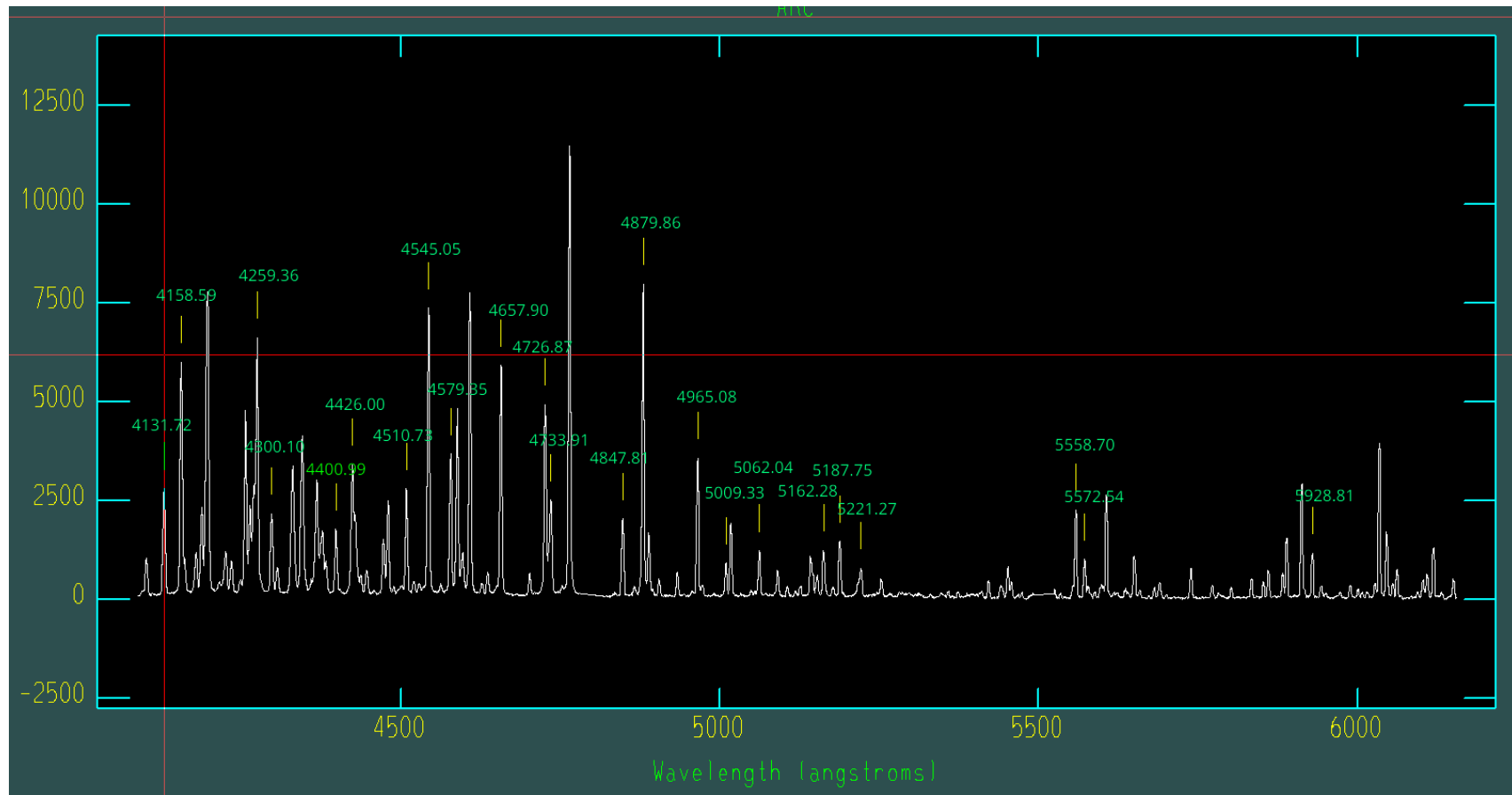


Figure C.2: Identification screen for the Copper-Argon (CuAr) ARC lamp for PG1300 SALT RSS data. The spectral lines that were identified are indicated with the yellow lines and their corresponding wavelength in Angstrom is shown in green.

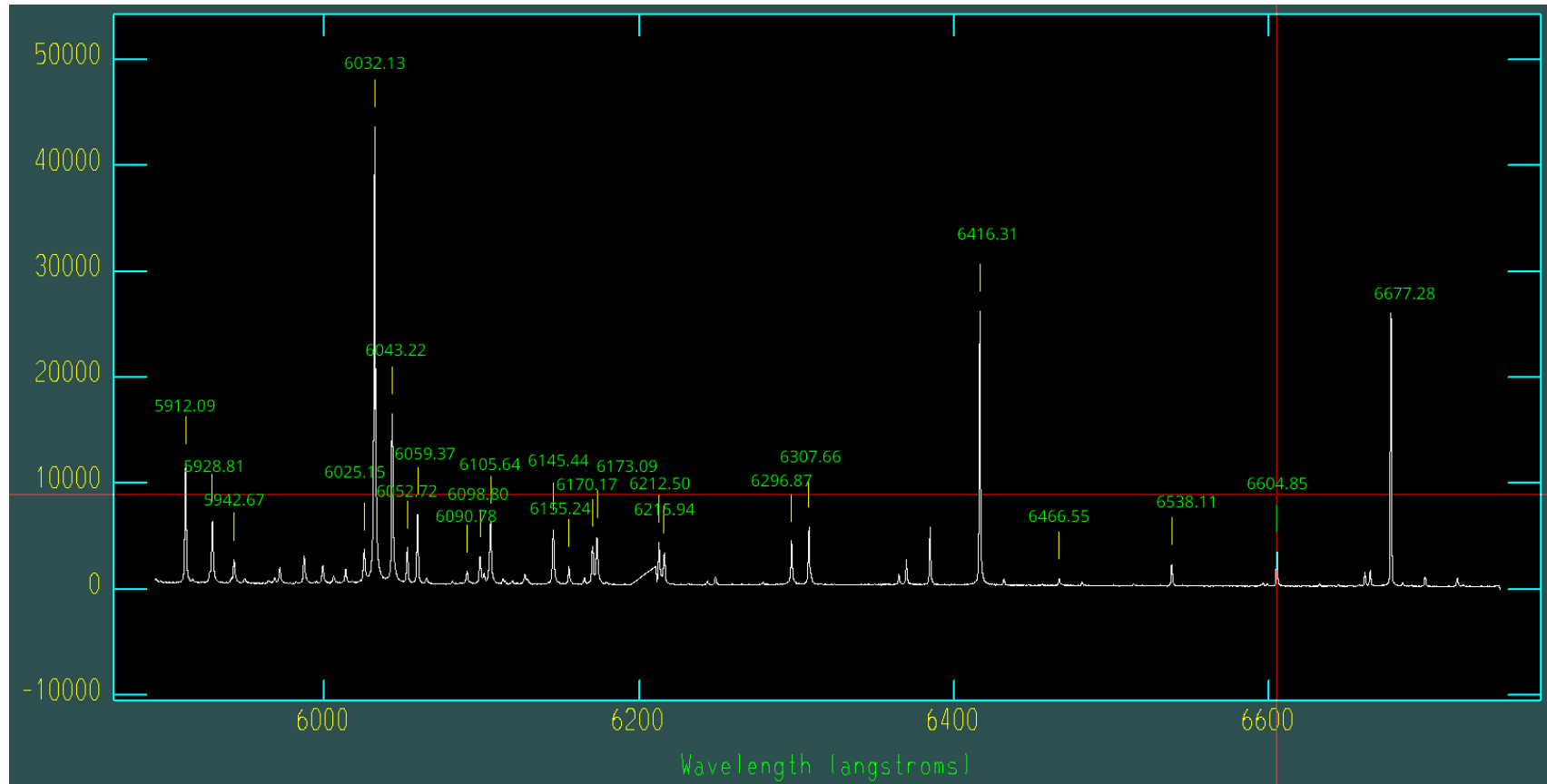


Figure C.3: Identification screen for the Argon (Ar) ARC lamp for PG2300 SALT RSS data. The spectral lines that were identified are indicated with the yellow lines and their corresponding wavelength in Angstrom is shown in green.

Appendix D

Spatially-resolved Stellar Kinematics of the CLoGS BGEs

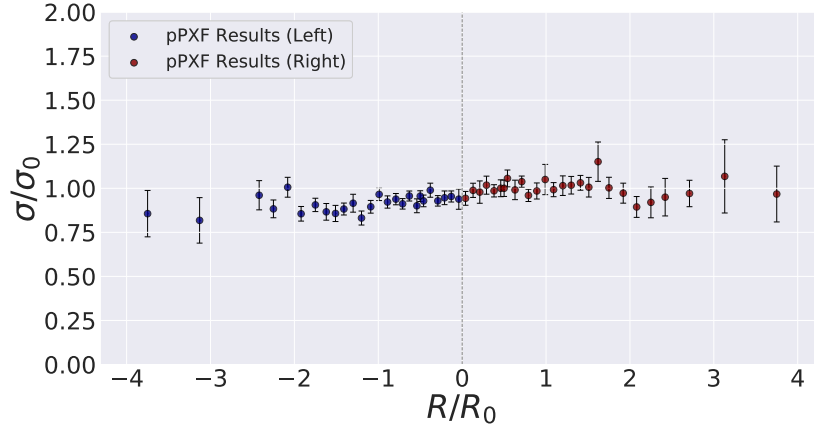


Figure D.1: Stellar velocity dispersion profile of ESO 507-25. The profile is approximately symmetric about the galactic centre and flat overall.

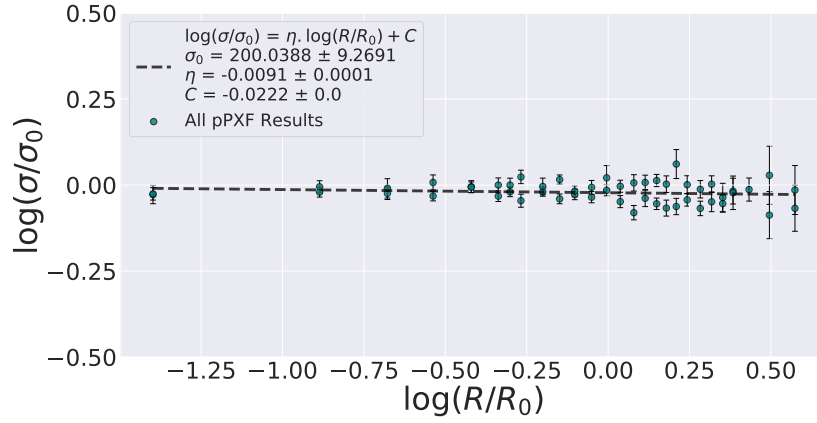


Figure D.2: Stellar velocity dispersion slope of ESO 507-25. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

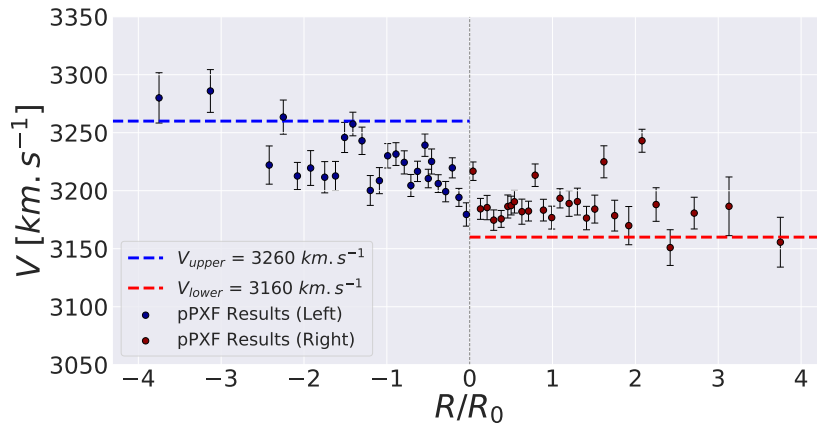


Figure D.3: Rotational velocity profile of ESO 507-25. The pPXF results show that ESO 507-25 has a minor amount of rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 50 \text{ km.s}^{-1}$.

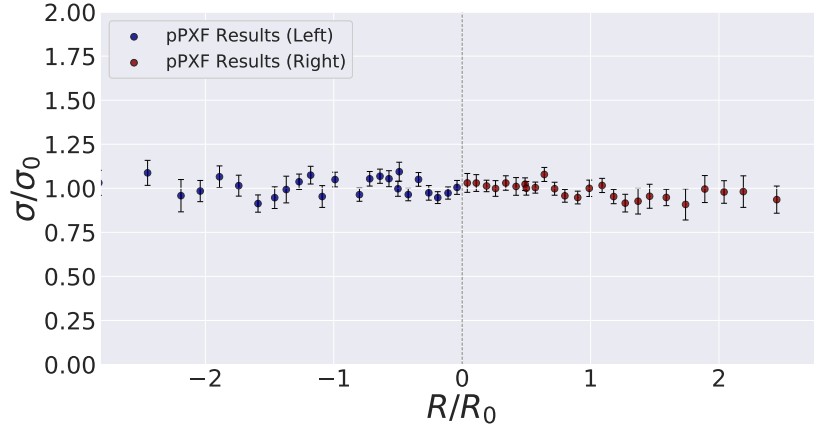


Figure D.4: Stellar velocity dispersion profile of NGC 1395. The profile is approximately symmetric about the galactic centre and flat overall.

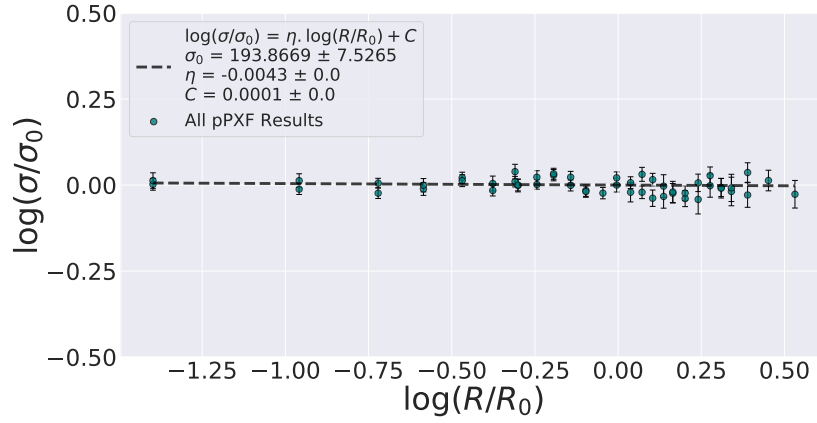


Figure D.5: Stellar velocity dispersion slope of NGC 1395. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

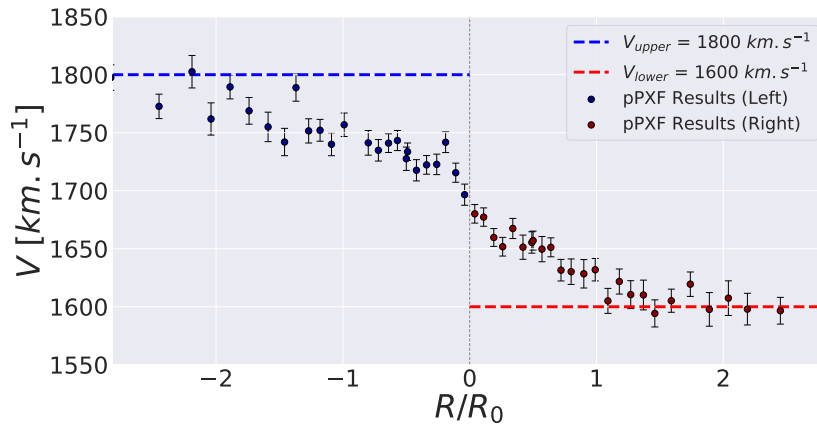


Figure D.6: Rotational velocity profile of NGC 1395. The pPXF results show that NGC 1395 has strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 100 \text{ km.s}^{-1}$.

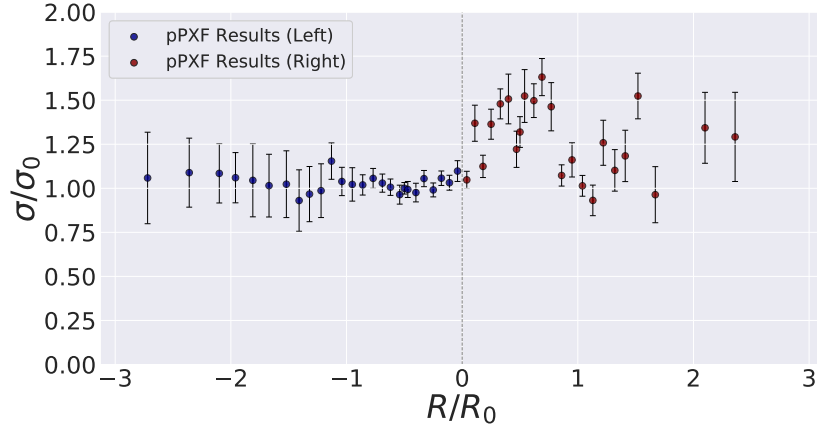


Figure D.7: Stellar velocity dispersion profile of NGC 1550. The right-hand side is noisy with a slightly higher velocity dispersion, presumably due to foreground stars.

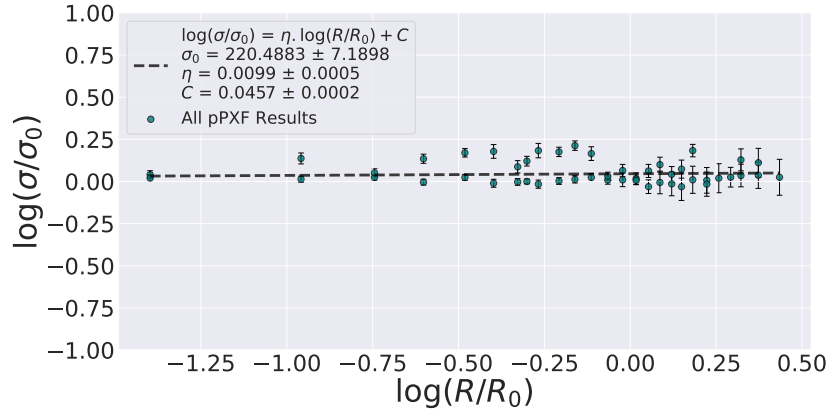


Figure D.8: Stellar velocity dispersion slope of NGC 1550. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

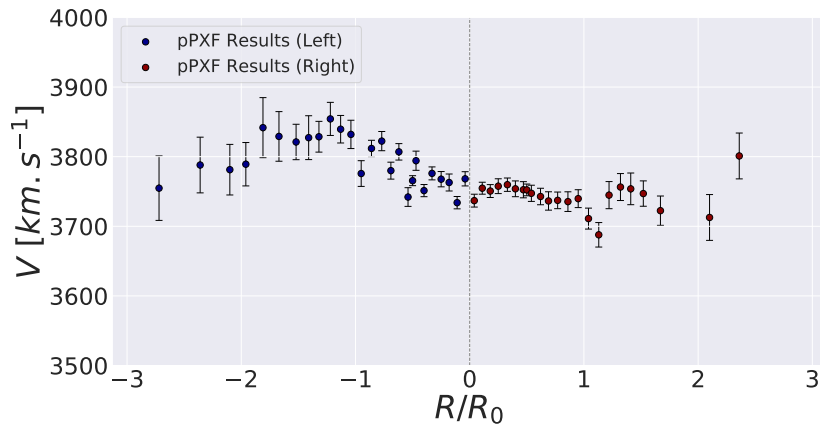


Figure D.9: Rotational velocity profile of NGC 1550. The pPXF results show that NGC 1550 has no clearly discernible rotation.

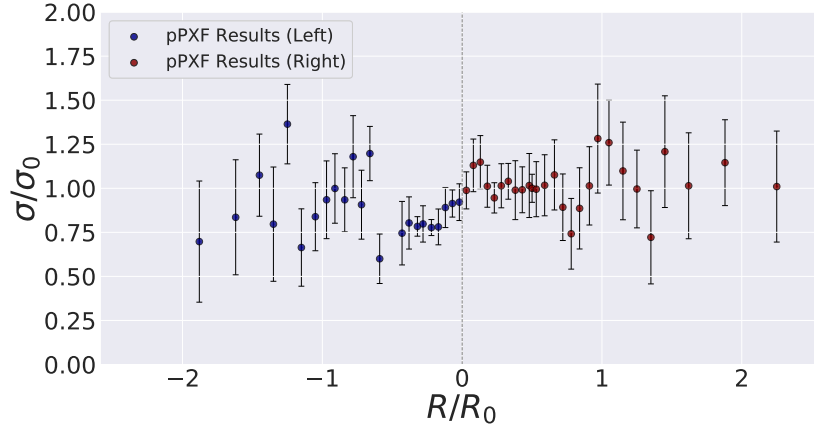


Figure D.10: Stellar velocity dispersion profile of NGC 2292.

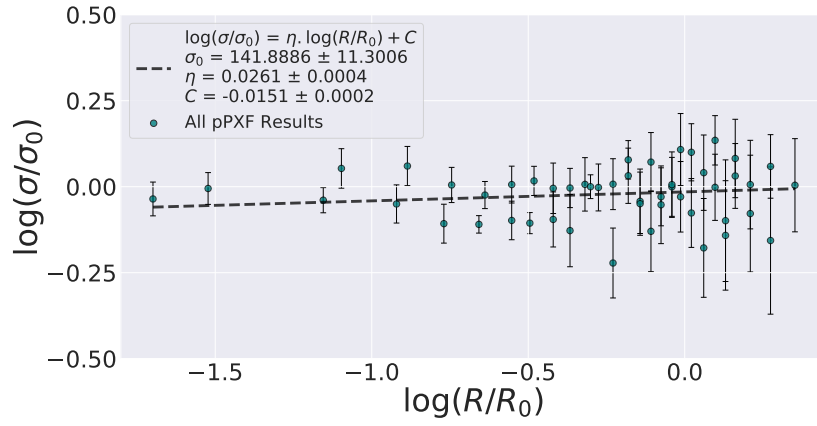


Figure D.11: Stellar velocity dispersion slope of NGC 2292. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

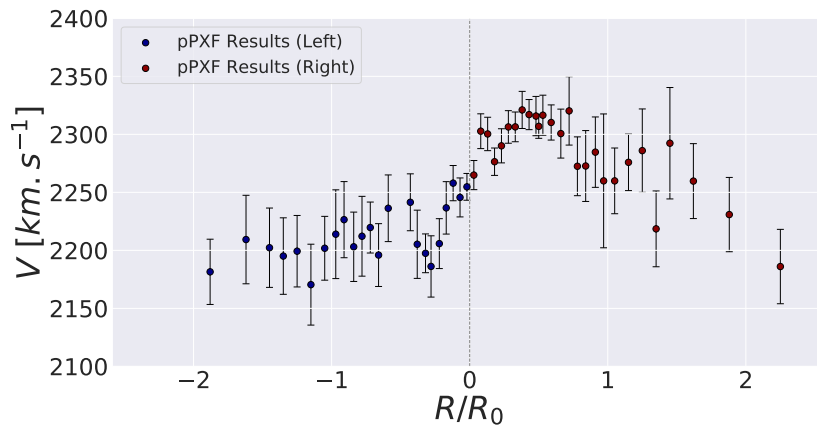


Figure D.12: Rotational velocity profile of NGC 2292. The pPXF results show that NGC 2292 has no clearly discernible rotation.

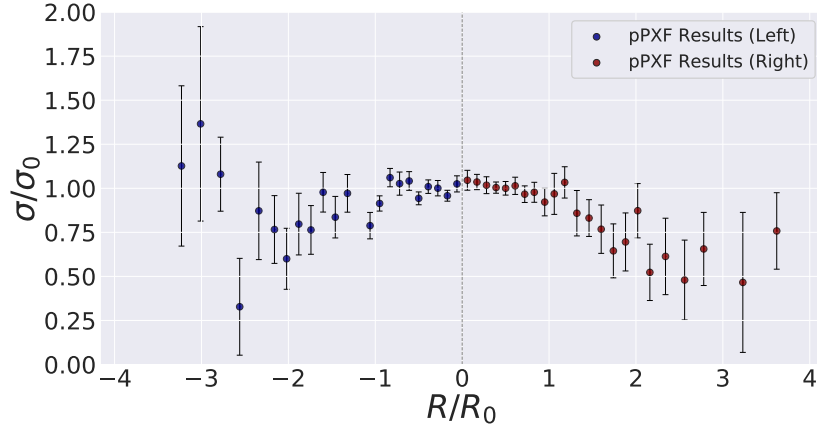


Figure D.13: Stellar velocity dispersion profile of NGC 2293. The profile is particularly noisy towards the outskirts in a symmetric fashion about the galactic centre.

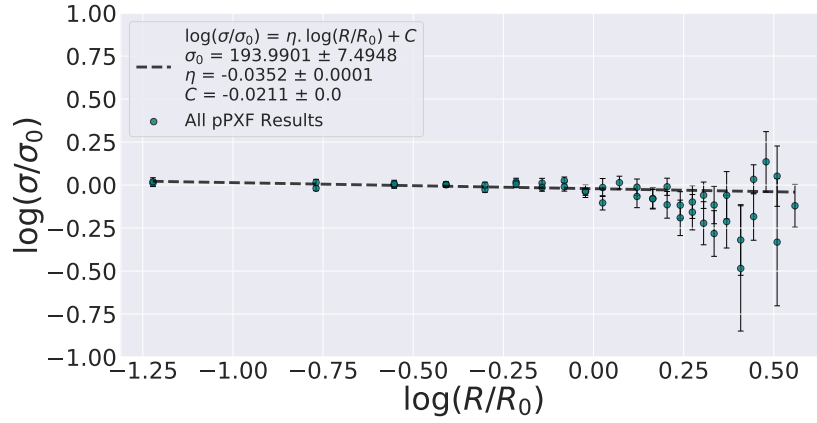


Figure D.14: Stellar velocity dispersion slope of NGC 2293. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

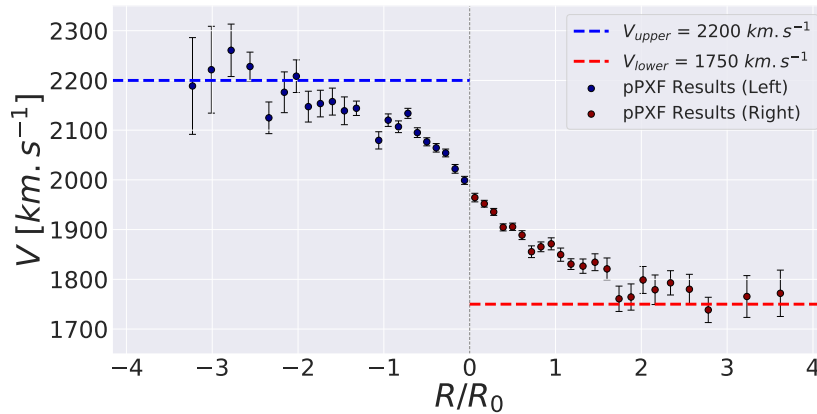


Figure D.15: Rotational velocity profile of NGC 2293. The pPXF results show that NGC 2293 has very strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 225 \text{ km.s}^{-1}$.

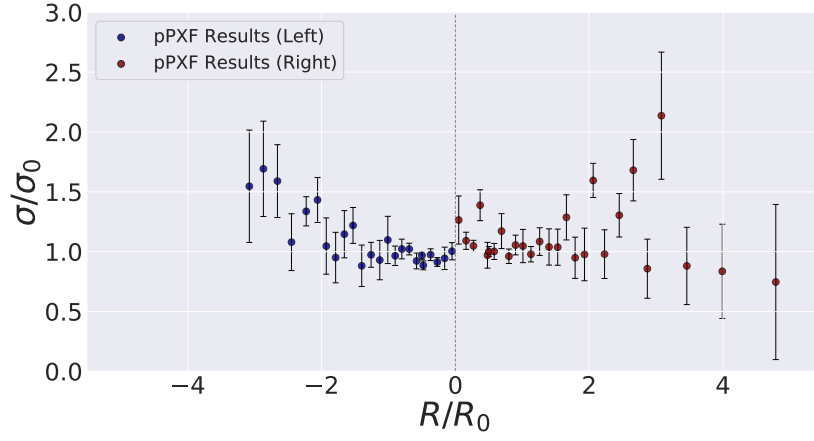


Figure D.16: Stellar velocity dispersion profile of NGC 2911.

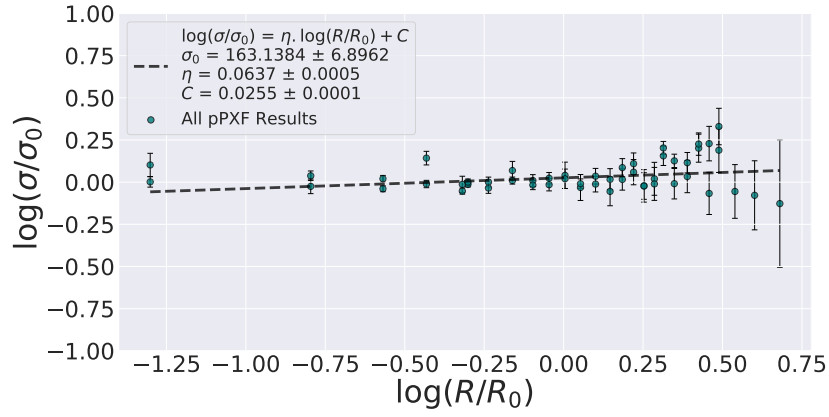


Figure D.17: Stellar velocity dispersion slope of NGC 2911. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

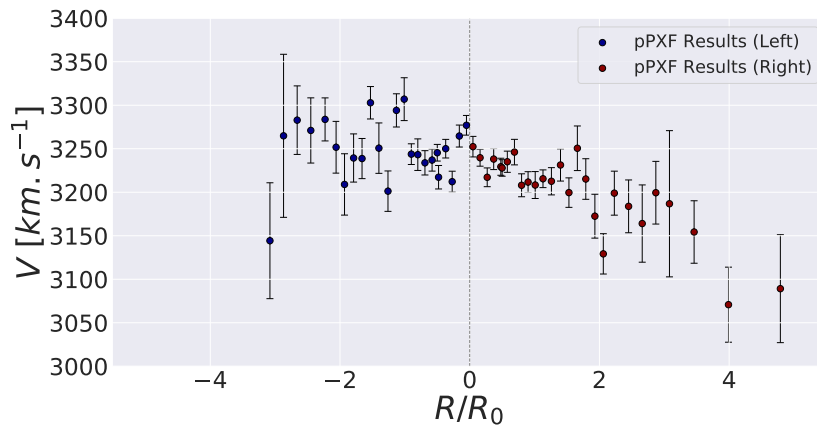


Figure D.18: Rotational velocity profile of NGC 2911. The pPXF results show that NGC 2911 has no clearly discernible rotation.

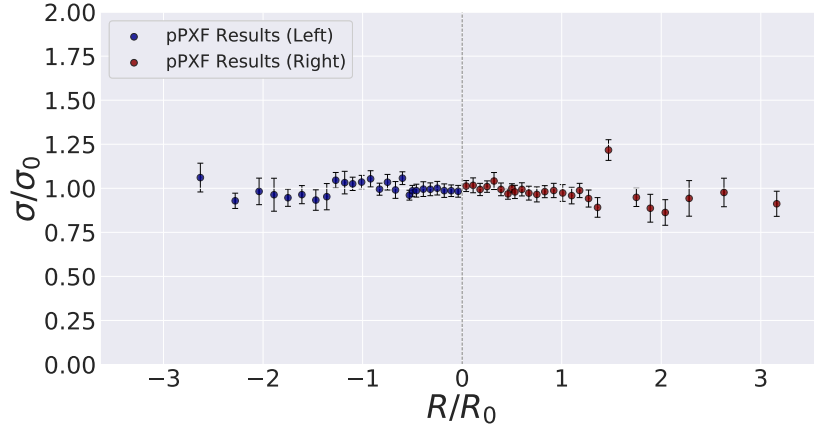


Figure D.19: Stellar velocity dispersion profile of NGC 3078. The profile is approximately symmetric about the galactic centre and flat overall.

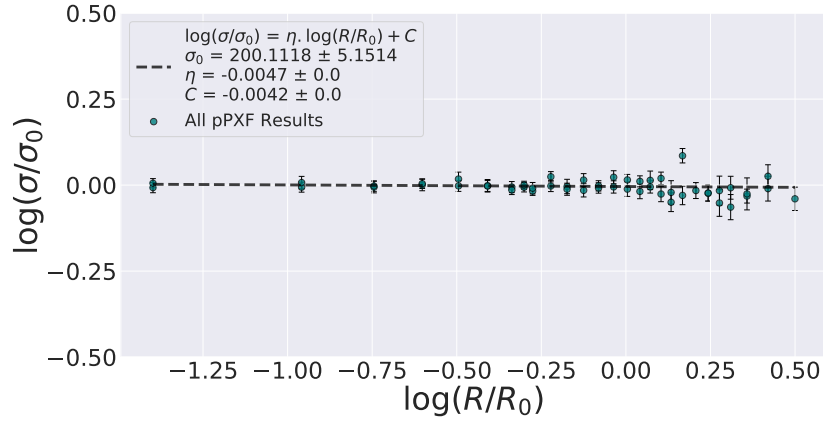


Figure D.20: Stellar velocity dispersion slope of NGC 3078. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

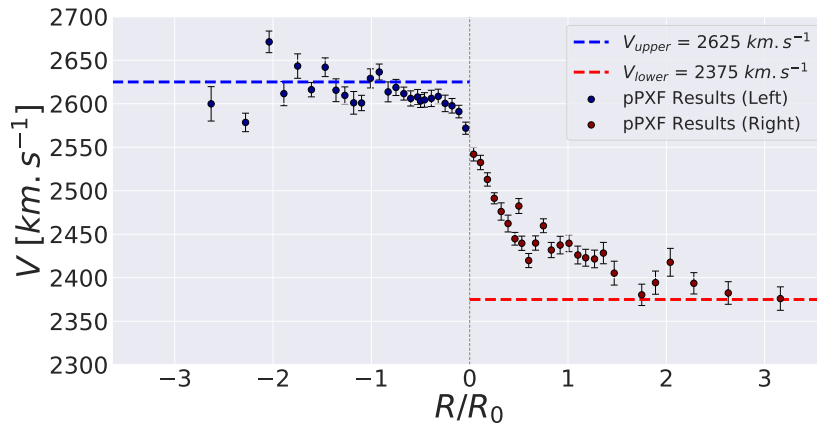


Figure D.21: Rotational velocity profile of NGC 3078. The pPXF results show that NGC 3078 has very strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 125 \text{ km.s}^{-1}$.

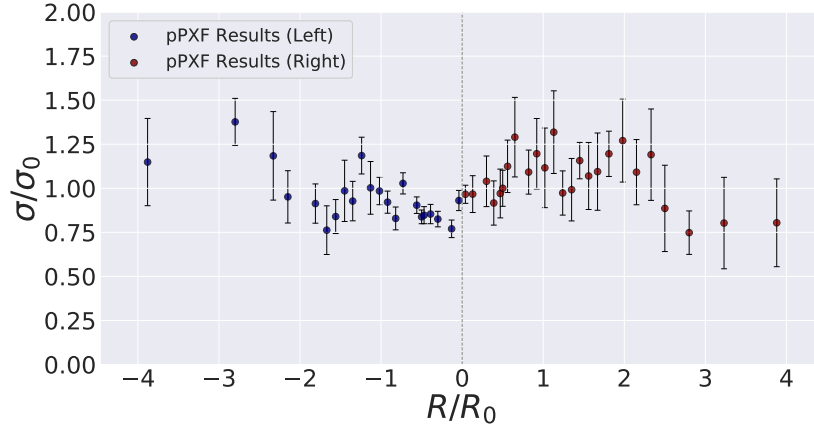


Figure D.22: Stellar velocity dispersion profile of NGC 3325.

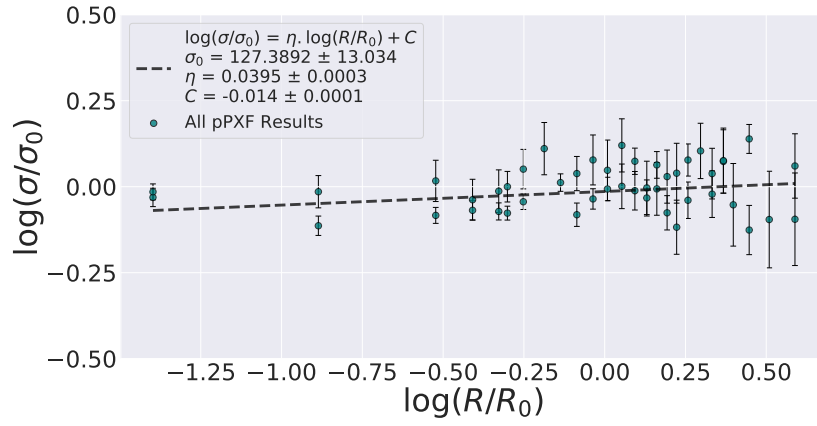


Figure D.23: Stellar velocity dispersion slope of NGC 3325. The slope is small and positive; however, the profile can be interpreted as flat with reasonable certainty.

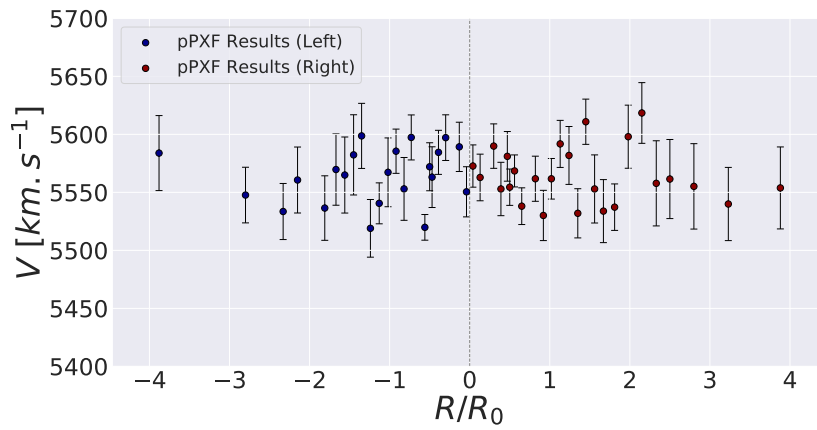


Figure D.24: Rotational velocity profile of NGC 3325. The pPXF results show that NGC 3325 has no clearly discernible rotation.

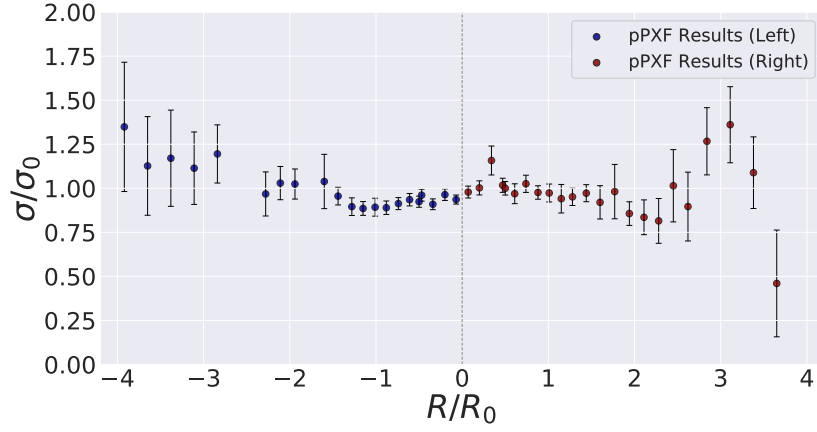


Figure D.25: Stellar velocity dispersion profile of NGC 3923. The profile is approximately symmetric about the galactic centre and flat overall.

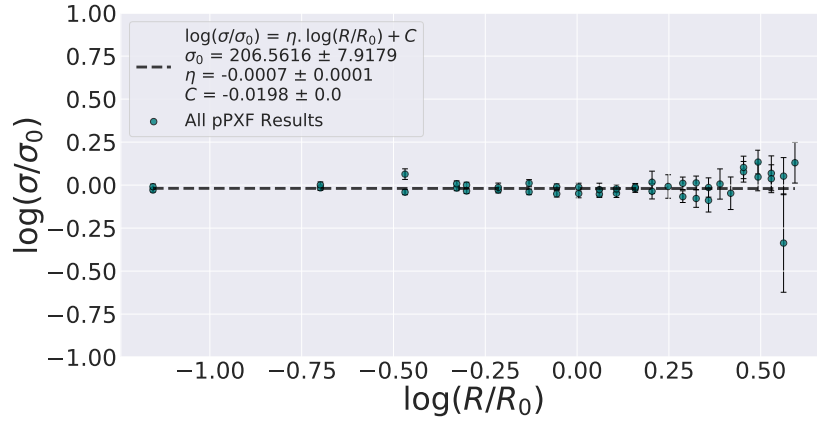


Figure D.26: Stellar velocity dispersion slope of NGC 3923. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

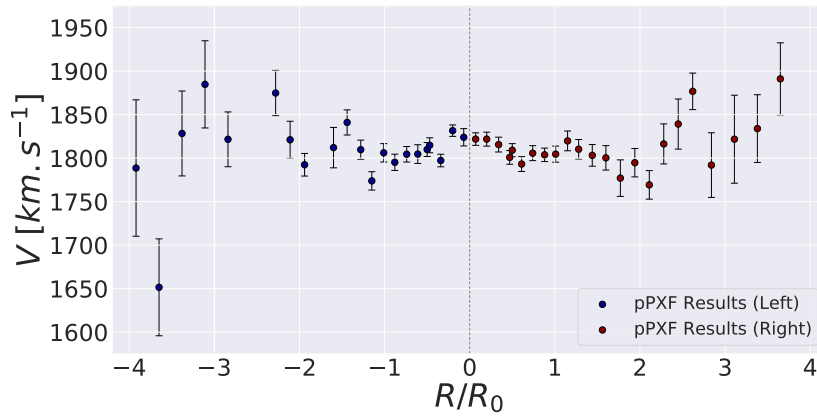


Figure D.27: Rotational velocity profile of NGC 3923. The pPXF results show that NGC 3923 has no clearly discernible rotation.

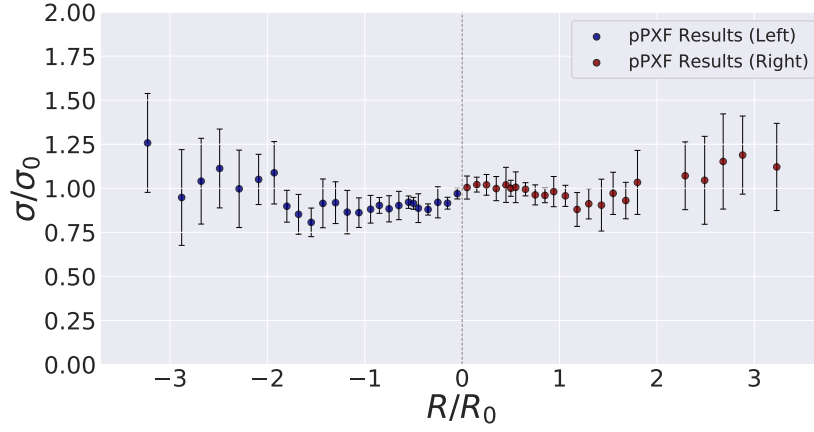


Figure D.28: Stellar velocity dispersion profile of NGC 4697. The profile is approximately symmetric about the galactic centre and flat overall.

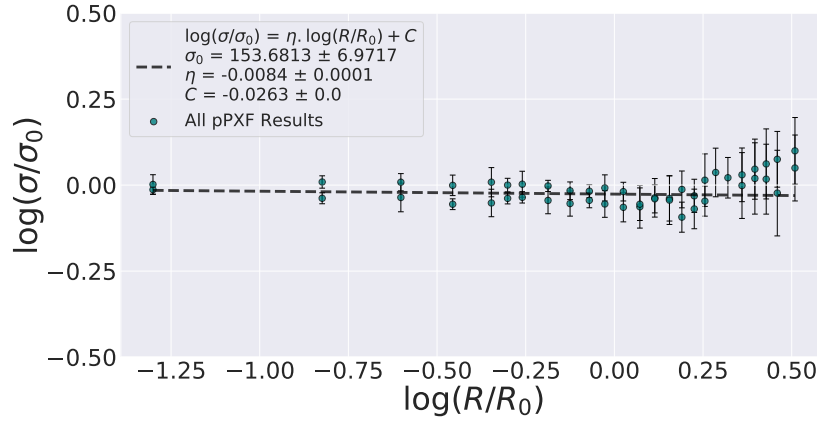


Figure D.29: Stellar velocity dispersion slope of NGC 4697. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

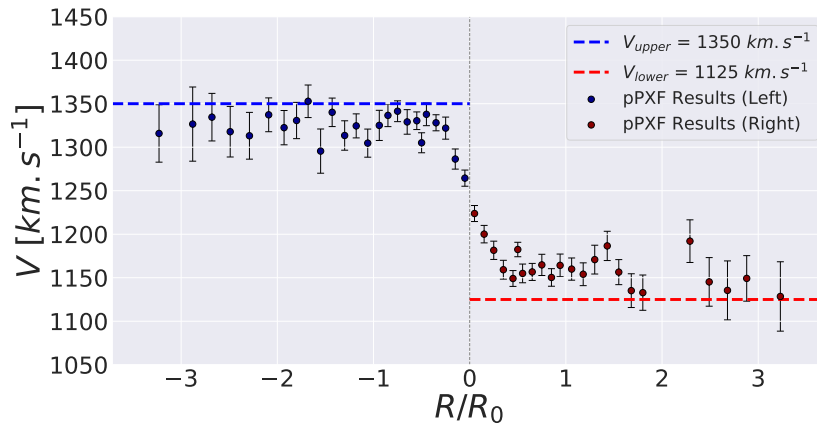


Figure D.30: Rotational velocity profile of NGC 4697. The pPXF results show that NGC 4697 has very strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 112 \text{ km.s}^{-1}$.

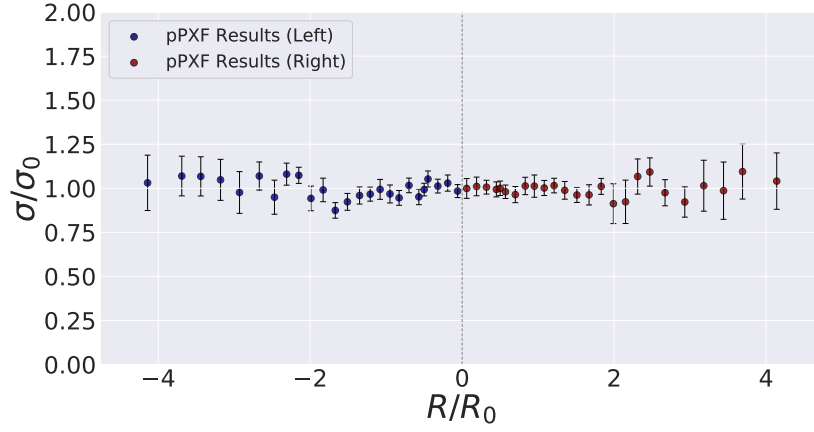


Figure D.31: Stellar velocity dispersion profile of NGC 5044. The profile is approximately symmetric about the galactic centre and flat overall.

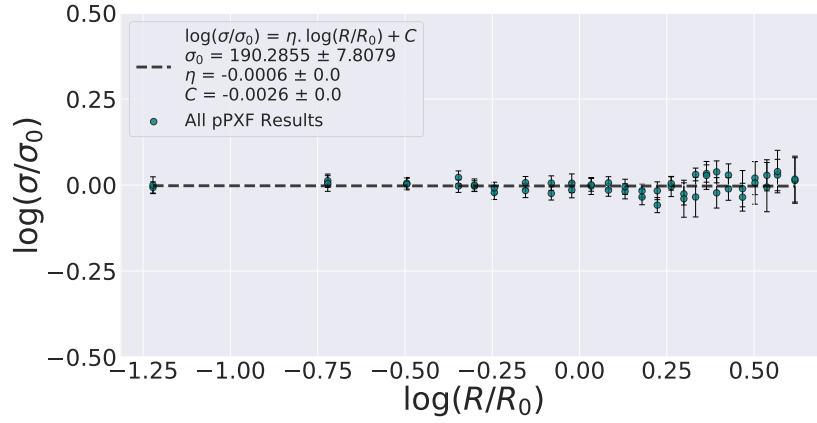


Figure D.32: Stellar velocity dispersion slope of NGC 5044. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

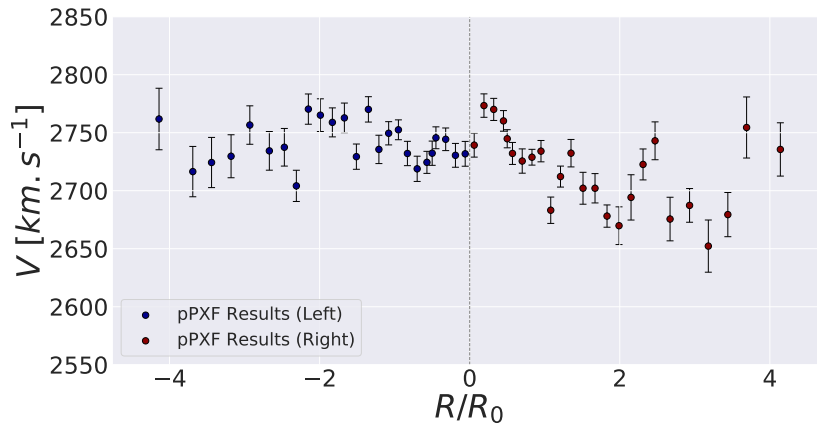


Figure D.33: Rotational velocity profile of NGC 5044. The pPXF results show that NGC 5044 has no clearly discernible rotation.

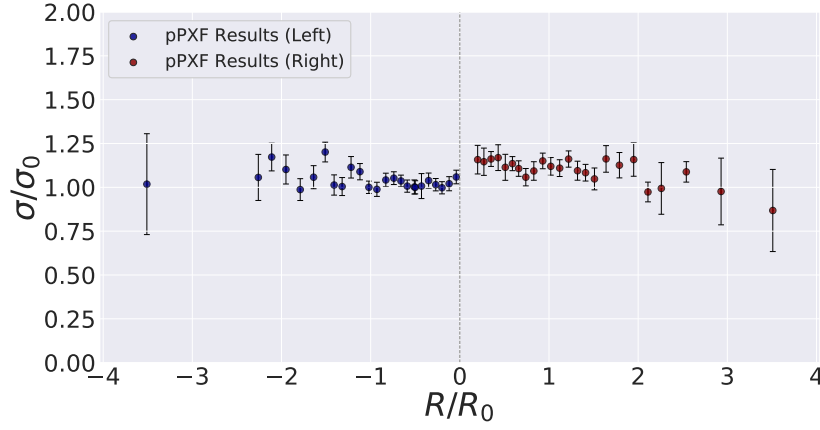


Figure D.34: Stellar velocity dispersion profile of NGC 5061. The profile is approximately symmetric about the galactic centre and flat overall.

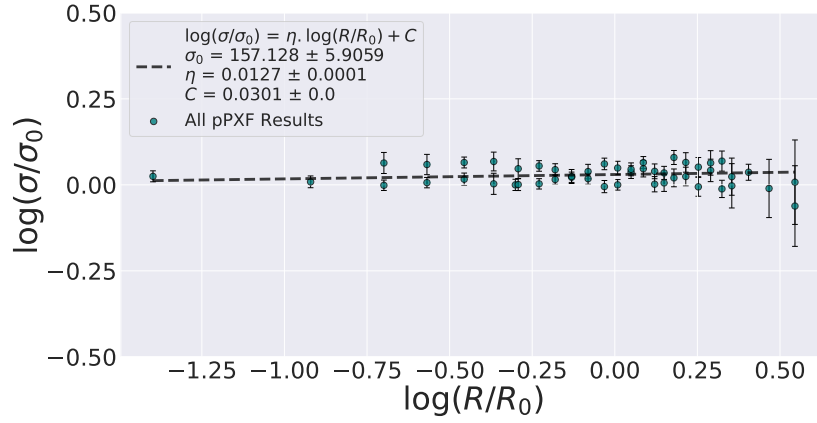


Figure D.35: Stellar velocity dispersion slope of NGC 5061. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

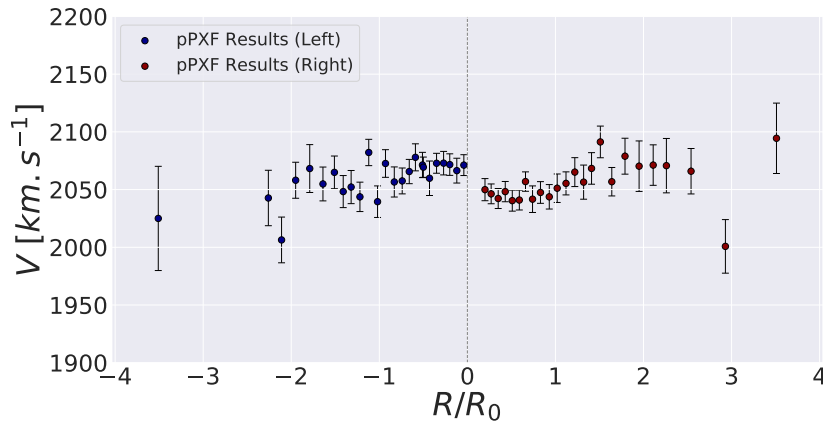


Figure D.36: Rotational velocity profile of NGC 5061. The pPXF results show that NGC 5061 has no clearly discernible rotation.

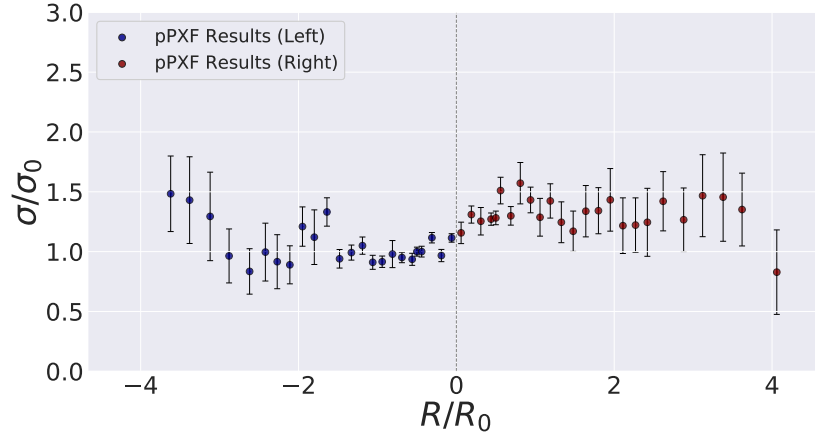


Figure D.37: Stellar velocity dispersion profile of NGC 5152.

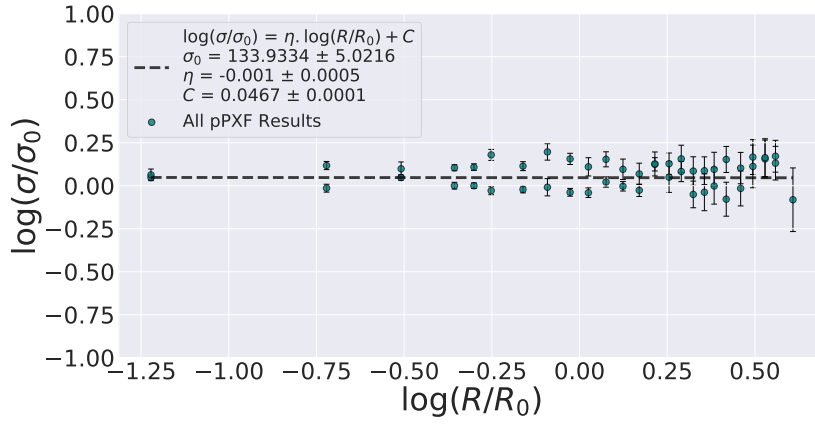


Figure D.38: Stellar velocity dispersion slope of NGC 5152. The slope is small and negative; however, the profile can be interpreted as flat with reasonable certainty.

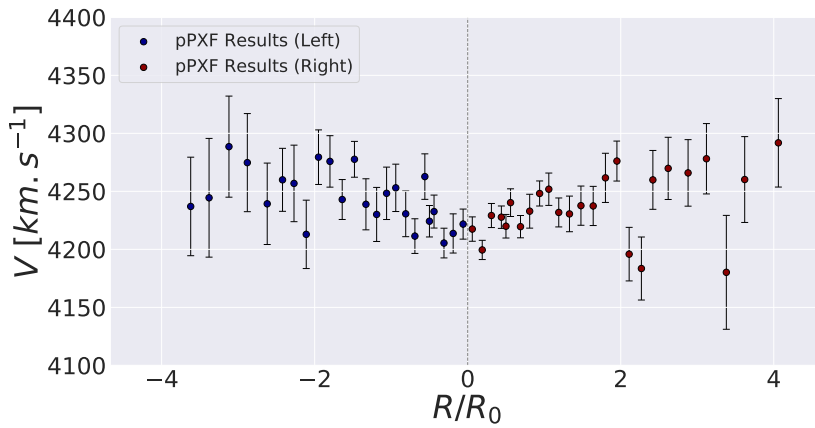


Figure D.39: Rotational velocity profile of NGC 5152. The pPXF results show that NGC 5152 has no clearly discernible rotation.

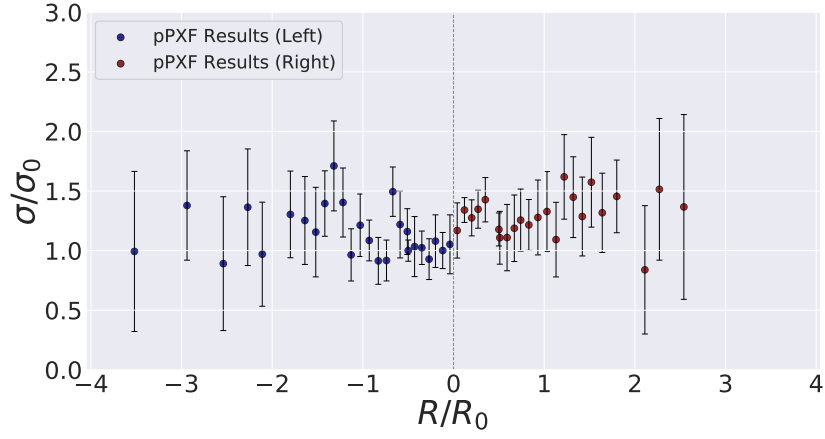


Figure D.40: Stellar velocity dispersion profile of NGC 5153.

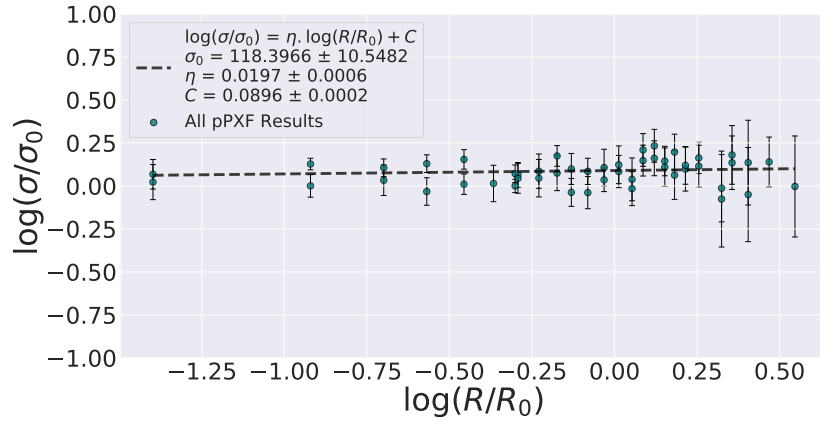
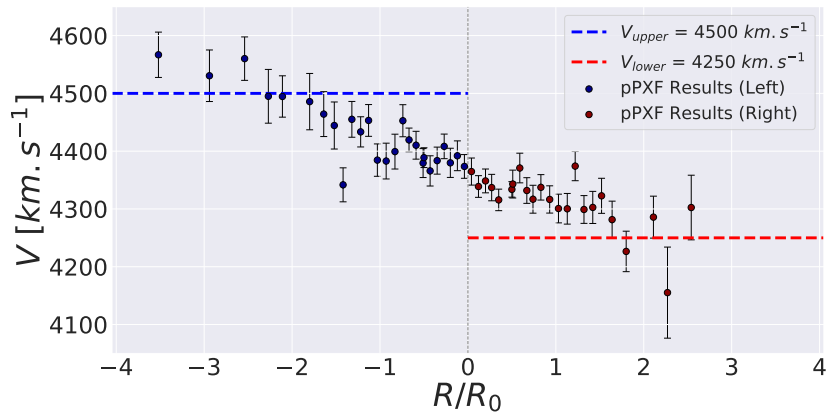


Figure D.41: Stellar velocity dispersion slope of NGC 5153. The slope is close to zero; however, the profile can be interpreted as flat with reasonable certainty.


 Figure D.42: Rotational velocity profile of NGC 5153. The pPXF results show that NGC 5153 has strong rotation with $V_{max} = (V_{upper} - V_{lower})/2 \approx 125 \text{ km.s}^{-1}$.

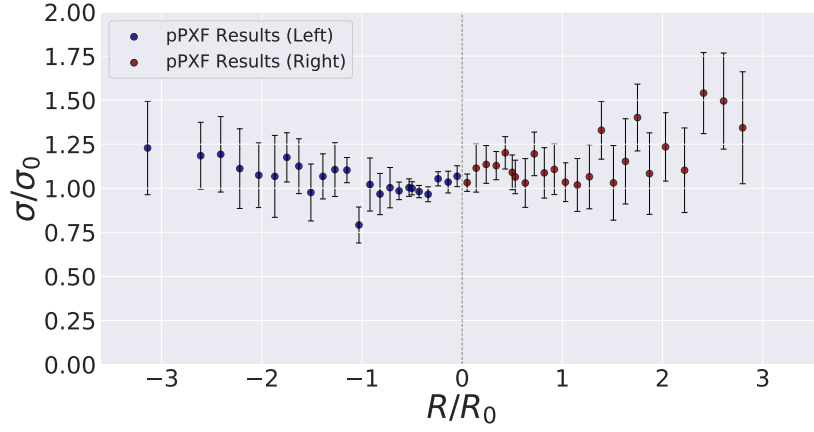


Figure D.43: Stellar velocity dispersion profile of NGC 5903.

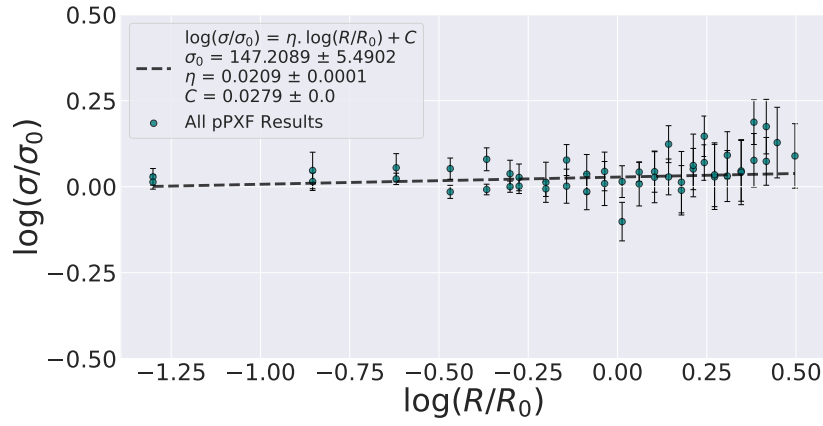


Figure D.44: Stellar velocity dispersion slope of NGC 5903. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

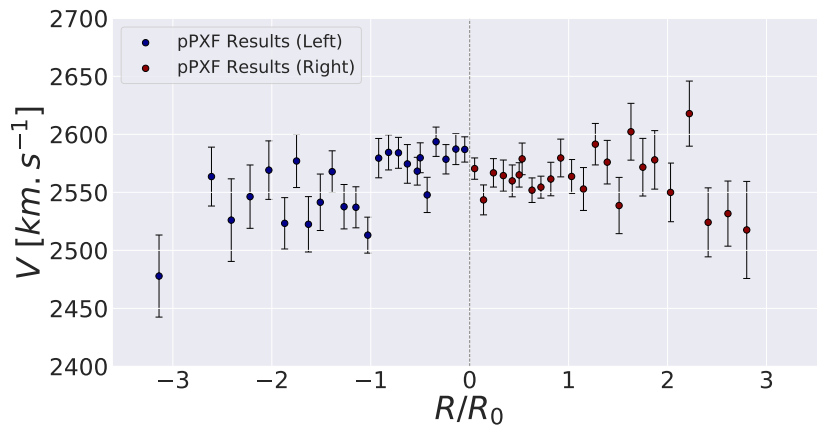


Figure D.45: Rotational velocity profile of NGC 5903. The pPXF results show that NGC 5903 has no clearly discernible rotation.

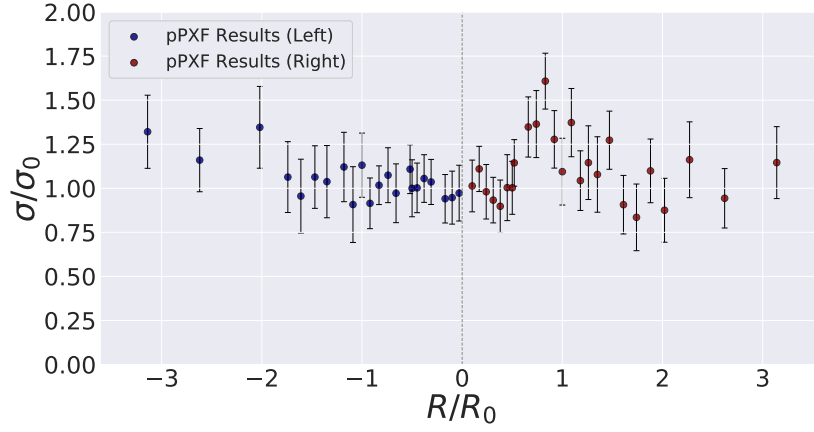


Figure D.46: Stellar velocity dispersion profile of NGC 7252.

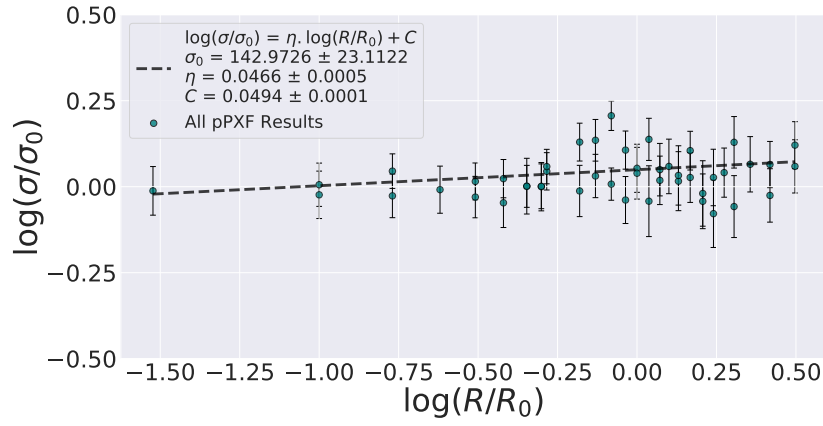


Figure D.47: Stellar velocity dispersion slope of NGC 7252. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

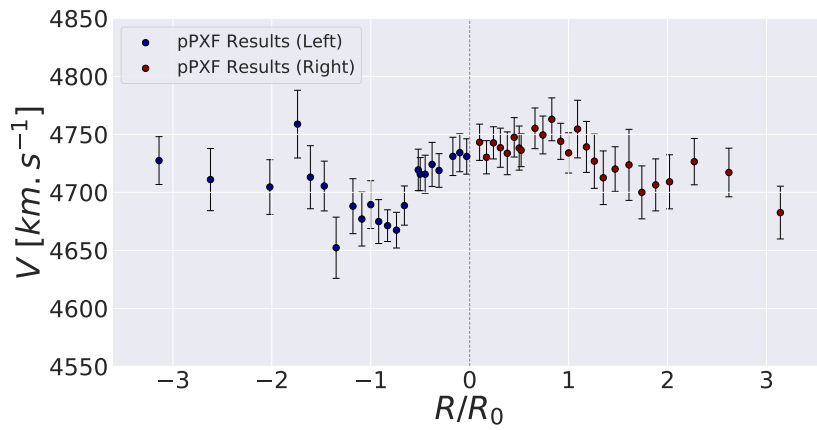


Figure D.48: Rotational velocity profile of NGC 7252. The pPXF results show that NGC 7252 has no clearly discernible rotation.

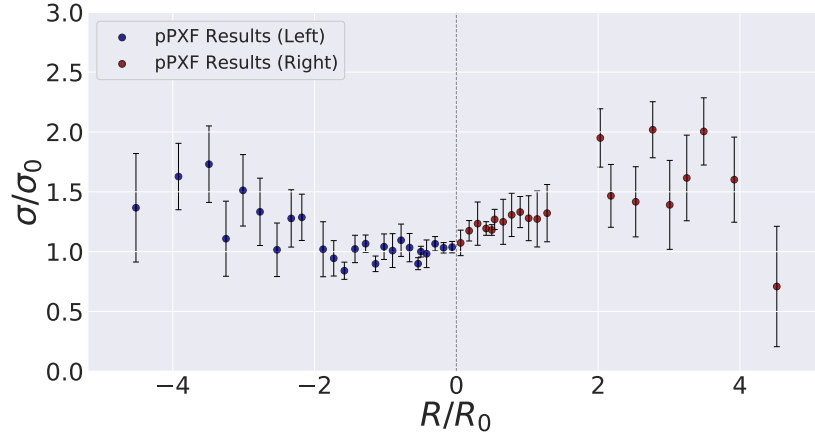


Figure D.49: Stellar velocity dispersion profile of NGC 7377.

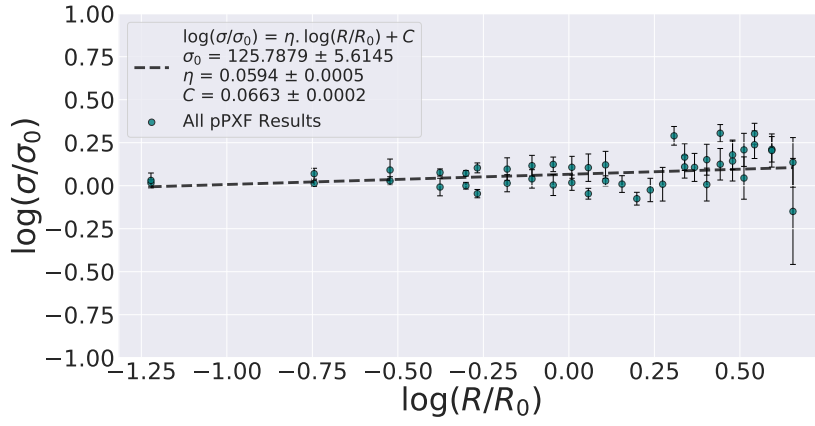


Figure D.50: Stellar velocity dispersion slope of NGC 7377. The slope is close to zero. The profile can be interpreted as flat with reasonable certainty.

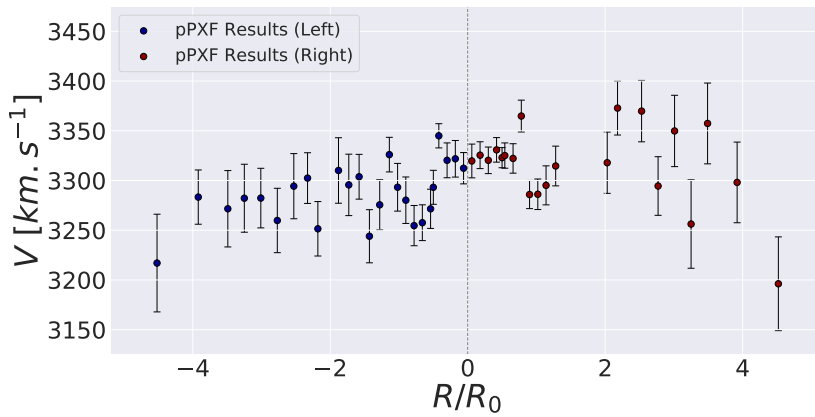


Figure D.51: Rotational velocity profile of NGC 7377. The pPXF results show that NGC 7377 has no clearly discernible rotation.

Appendix E

Stellar Population Properties of the CLoGS BGEs

Table E.1: Luminosity weighted stellar population properties of NGC 128's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.937	1	$9.0^{+1.05}_{-1.11}$	$-0.33^{+0.07}_{-0.02}$	82.51	97.23
			2	$0.6^{+1.01}_{-1.02}$	$0.35^{+0.01}_{-0.0}$	17.49	2.77
	Outer	0.4	1	$9.0^{+1.03}_{-1.03}$	$-0.33^{+0.04}_{-0.01}$	33.33	38.94
			2	$12.0^{+1.03}_{-1.03}$	$-0.33^{+0.04}_{-0.01}$	33.33	50.76
			3	$3.0^{+1.02}_{-1.01}$	$-0.33^{+0.02}_{-0.01}$	16.67	7.66
			4	$0.6^{+1.02}_{-1.01}$	$0.35^{+0.02}_{-0.01}$	16.67	2.64
STELIB	Inner	1.018	1	$8.0^{+1.02}_{-1.08}$	$-0.33^{+0.03}_{-0.01}$	33.0	47.96
			2	$4.0^{+1.02}_{-1.08}$	$0.0^{+0.03}_{-0.01}$	33.0	30.22
			3	$2.0^{+1.02}_{-1.08}$	$0.35^{+0.03}_{-0.01}$	33.0	21.65
			4	$0.5^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.17
	Outer	0.431	1	$8.0^{+1.03}_{-1.06}$	$-0.33^{+0.02}_{-0.0}$	33.0	47.96
			2	$4.0^{+1.03}_{-1.06}$	$0.0^{+0.02}_{-0.0}$	33.0	30.31
			3	$2.0^{+1.03}_{-1.06}$	$0.35^{+0.02}_{-0.0}$	33.0	21.64
			4	$0.2^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.09
ELODIE	Inner	1.105	1	$3.0^{+1.11}_{-1.03}$	$-0.33^{+0.05}_{-0.06}$	79.21	90.99
			2	$0.7^{+1.03}_{-1.01}$	$0.35^{+0.01}_{-0.02}$	19.8	9.0
			3	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.01
	Outer	0.502	1	$4.0^{+1.04}_{-1.19}$	$0.0^{+0.04}_{-0.0}$	90.91	90.35
			2	$9.0^{+1.0}_{-1.02}$	$-2.25^{+0.0}_{-0.0}$	9.09	9.65
E-MaStar	Inner	0.003	1	$1.0^{+1.52}_{-1.22}$	$0.35^{+0.0}_{-0.02}$	50.0	29.74
			2	$5.0^{+1.52}_{-1.22}$	$-0.7^{+0.0}_{-0.02}$	50.0	70.26
	Outer	0.003	1	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	2.62
			2	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	50.0	97.38
Th-MaStar	Inner	0.003	1	$1.0^{+1.52}_{-1.22}$	$0.35^{+0.0}_{-0.02}$	50.0	29.74
			2	$5.0^{+1.52}_{-1.22}$	$-0.7^{+0.0}_{-0.02}$	50.0	70.26
	Outer	0.003	1	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	2.62
			2	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	50.0	97.38

Table E.2: Luminosity weighted stellar population properties of NGC 193's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.253	1	$12.0^{+1.04}_{-1.0}$	$-0.33^{+0.0}_{-0.06}$	45.45	45.16
			2	$13.0^{+1.04}_{-1.0}$	$-0.33^{+0.0}_{-0.06}$	45.45	48.67
			3	$5.0^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	6.18
	Outer	0.166	1	$6.0^{+1.01}_{-1.04}$	$-0.33^{+0.02}_{-0.0}$	60.61	44.85
			2	$11.0^{+1.01}_{-1.02}$	$0.0^{+0.01}_{-0.0}$	30.3	46.56
			3	$8.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	9.09	8.59
STELIB	Inner	0.386	1	$10.0^{+1.05}_{-1.01}$	$-0.33^{+0.0}_{-0.04}$	90.91	94.07
			2	$5.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	9.09	5.93
	Outer	0.176	1	$7.0^{+1.01}_{-1.06}$	$-0.33^{+0.02}_{-0.01}$	50.0	37.11
			2	$10.0^{+1.01}_{-1.06}$	$0.0^{+0.01}_{-0.01}$	45.45	56.08
			3	$12.0^{+1.0}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	4.55	6.81
	Inner	0.434	1	$8.0^{+1.02}_{-1.08}$	$-0.33^{+0.01}_{-0.01}$	99.01	100.0
ELODIE	Outer	0.154	2	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.0
			1	$10.0^{+1.08}_{-1.03}$	$-0.33^{+0.01}_{-0.09}$	49.5	40.61
			2	$12.0^{+1.08}_{-1.03}$	$0.0^{+0.01}_{-0.09}$	49.5	58.79
	Inner	0.001	3	$13.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.6
			1	$8.0^{+1.07}_{-1.0}$	$0.0^{+0.0}_{-0.04}$	90.91	98.22
			2	$1.0^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	9.09	1.78
E-MaStar	Outer	0.002	1	$11.0^{+1.0}_{-1.1}$	$-0.33^{+0.08}_{-0.0}$	99.9	100.0
			2	$0.03^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	0.1	0.0
	Inner	0.001	1	$8.0^{+1.07}_{-1.0}$	$0.0^{+0.0}_{-0.04}$	90.91	98.22
			2	$1.0^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	9.09	1.78
	Outer	0.002	1	$11.0^{+1.0}_{-1.1}$	$-0.33^{+0.08}_{-0.0}$	99.9	100.0
			2	$0.03^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	0.1	0.0
Th-MaStar	Inner	0.001	1	$8.0^{+1.07}_{-1.0}$	$0.0^{+0.0}_{-0.04}$	90.91	98.22
	Outer	0.002	1	$11.0^{+1.0}_{-1.1}$	$-0.33^{+0.08}_{-0.0}$	99.9	100.0
			2	$0.03^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	0.1	0.0

Table E.3: Luminosity weighted stellar population properties of NGC 1395's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.481	1	$13.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	50.0	65.44
			2	$4.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	50.0	34.56
STELIB	Outer	0.13	1	$11.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	98.85
			2	$1.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	1.15
	Inner	0.633	1	$12.0^{+1.01}_{-1.08}$	$0.0^{+0.03}_{-0.02}$	68.18	89.46
			2	$0.6^{+1.0}_{-1.03}$	$0.35^{+0.01}_{-0.01}$	22.73	2.71
			3	$7.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	4.55	3.0
			4	$12.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	4.55	4.82
	Outer	0.216	1	$7.0^{+1.02}_{-1.07}$	$-0.33^{+0.01}_{-0.01}$	66.6	84.27
			2	$1.5^{+1.01}_{-1.03}$	$0.35^{+0.01}_{-0.01}$	33.3	15.72
3			$0.03^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.1	0.0	
ELODIE	Inner	0.682	1	$12.0^{+1.0}_{-1.04}$	$0.35^{+0.02}_{-0.01}$	45.0	63.01
			2	$13.0^{+1.0}_{-1.02}$	$-0.33^{+0.01}_{-0.0}$	22.5	21.08
			3	$4.0^{+1.0}_{-1.01}$	$-0.33^{+0.01}_{-0.0}$	12.5	4.35
			4	$1.5^{+1.0}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	10.0	1.72
			5	$11.0^{+1.0}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	10.0	9.84
	Outer	0.272	1	$3.0^{+1.01}_{-1.05}$	$-0.33^{+0.09}_{-0.0}$	33.0	22.78
			2	$10.0^{+1.01}_{-1.05}$	$-0.33^{+0.09}_{-0.0}$	33.0	62.92
			3	$1.5^{+1.01}_{-1.05}$	$0.0^{+0.09}_{-0.0}$	33.0	14.29
			4	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.02
			Inner	0.004	1	$2.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$
	2	$0.01^{+1.0}_{-1.0}$			$-0.33^{+0.0}_{-0.0}$	9.09	0.49
	Outer	0.001	1	$3.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.07}$	90.91	94.56
2			$0.9^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	5.44	
Th-MaStar	Inner	0.004	1	$2.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	90.91	99.51
			2	$0.01^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.49
	Outer	0.001	1	$3.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.07}$	90.91	94.56
			2	$0.9^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	5.44

Table E.4: Luminosity weighted stellar population properties of NGC 1550's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.427	1	$12.0^{+1.02}_{-1.03}$	$-0.33^{+0.0}_{-0.01}$	33.0	28.17
			2	$7.0^{+1.02}_{-1.03}$	$0.35^{+0.0}_{-0.01}$	33.0	26.24
			3	$12.0^{+1.02}_{-1.03}$	$0.35^{+0.0}_{-0.01}$	33.0	45.51
			4	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.08
	Outer	0.535	1	$11.0^{+1.01}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	50.5	59.76
			2	$12.0^{+1.01}_{-1.02}$	$-0.33^{+0.0}_{-0.0}$	49.5	40.24
			3	$11.0^{+1.03}_{-1.02}$	$0.35^{+0.01}_{-0.01}$	37.5	46.52
			4	$7.0^{+1.01}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	12.5	6.23
STELIB	Inner	0.467	1	$10.0^{+1.03}_{-1.02}$	$0.35^{+0.01}_{-0.01}$	37.5	41.83
			2	$11.0^{+1.03}_{-1.02}$	$0.35^{+0.01}_{-0.01}$	37.5	46.52
			3	$7.0^{+1.01}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	12.5	6.23
			4	$5.0^{+1.01}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	12.5	5.43
	Outer	0.581	1	$11.0^{+1.0}_{-1.02}$	$-0.33^{+0.0}_{-0.01}$	33.3	24.92
			2	$12.0^{+1.0}_{-1.02}$	$-0.33^{+0.0}_{-0.01}$	33.3	26.92
			3	$13.0^{+1.0}_{-1.02}$	$0.35^{+0.0}_{-0.01}$	33.3	48.16
			4	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.1	0.0
ELODIE	Inner	2.567	1	$7.0^{+1.04}_{-1.16}$	$0.0^{+0.03}_{-0.02}$	77.5	61.53
			2	$12.0^{+1.01}_{-1.04}$	$0.35^{+0.01}_{-0.0}$	22.5	38.47
	Outer	1.083	1	$13.0^{+1.0}_{-1.08}$	$0.35^{+0.0}_{-0.02}$	69.7	87.71
			2	$11.0^{+1.0}_{-1.03}$	$-2.25^{+0.0}_{-0.01}$	30.3	12.29
E-MaStar	Inner	0.001	1	$7.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.31
			2	$0.03^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.69
	Outer	0.002	1	$0.02^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	50.0	3.0
			2	$13.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	50.0	97.0
Th-MaStar	Inner	0.001	1	$7.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.31
			2	$0.03^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.69
	Outer	0.002	1	$0.02^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	50.0	3.0
			2	$13.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	50.0	97.0

Table E.5: Luminosity weighted stellar population properties of NGC 2292's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.496	1	$8.0^{+1.0}_{-1.46}$	$-0.33^{+0.15}_{-0.0}$	90.91	92.34
			2	$13.0^{+1.0}_{-1.04}$	$-2.25^{+0.02}_{-0.0}$	9.09	7.66
	Outer	1.531	1	$6.0^{+1.02}_{-1.13}$	$-1.35^{+0.18}_{-0.03}$	45.45	23.63
			2	$13.0^{+1.02}_{-1.13}$	$-0.33^{+0.18}_{-0.03}$	45.45	66.59
			3	$9.0^{+1.0}_{-1.02}$	$-0.33^{+0.04}_{-0.01}$	9.09	9.78
STELIB	Inner	0.559	1	$6.0^{+1.06}_{-1.14}$	$-0.33^{+0.1}_{-0.03}$	60.61	72.7
			2	$3.0^{+1.03}_{-1.07}$	$-0.33^{+0.05}_{-0.01}$	30.3	20.38
			3	$3.0^{+1.01}_{-1.02}$	$0.0^{+0.02}_{-0.0}$	9.09	6.91
	Outer	1.539	1	$11.0^{+1.07}_{-1.18}$	$-0.33^{+0.06}_{-0.12}$	49.5	92.01
			2	$0.4^{+1.07}_{-1.18}$	$0.35^{+0.06}_{-0.12}$	49.5	7.97
			3	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.02
ELODIE	Inner	1.024	1	$3.0^{+1.27}_{-1.15}$	$-0.33^{+0.0}_{-0.1}$	90.91	64.59
			2	$13.0^{+1.02}_{-1.01}$	$0.35^{+0.0}_{-0.01}$	9.09	35.41
	Outer	1.552	1	$11.0^{+1.07}_{-1.26}$	$-2.25^{+0.08}_{-0.13}$	60.61	40.41
			2	$12.0^{+1.03}_{-1.12}$	$0.35^{+0.04}_{-0.06}$	30.3	58.53
			3	$0.5^{+1.01}_{-1.03}$	$0.35^{+0.01}_{-0.02}$	9.09	1.06
E-MaStar	Inner	0.002	1	$2.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	90.91	99.65
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.35
	Outer	0.011	1	$9.0^{+1.04}_{-4.17}$	$-0.33^{+0.03}_{-0.3}$	50.0	68.33
			2	$13.0^{+1.04}_{-4.17}$	$-2.25^{+0.03}_{-0.3}$	50.0	31.67
Th-MaStar	Inner	0.002	1	$2.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	90.91	99.65
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.35
	Outer	0.011	1	$9.0^{+1.04}_{-4.17}$	$-0.33^{+0.03}_{-0.3}$	50.0	68.33
			2	$13.0^{+1.04}_{-4.17}$	$-2.25^{+0.03}_{-0.3}$	50.0	31.67

Table E.6: Luminosity weighted stellar population properties of NGC 2293's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.627	1	$12.0^{+1.03}_{-1.05}$	$-0.33^{+0.05}_{-0.02}$	74.26	70.88
			2	$9.0^{+1.01}_{-1.02}$	$0.35^{+0.02}_{-0.01}$	24.75	27.76
			3	$11.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	1.36
	Outer	1.61	1	$6.0^{+1.09}_{-1.12}$	$-0.33^{+0.04}_{-0.01}$	45.45	27.73
			2	$13.0^{+1.06}_{-1.07}$	$0.35^{+0.03}_{-0.01}$	27.27	51.98
			3	$8.0^{+1.05}_{-1.06}$	$-0.33^{+0.02}_{-0.01}$	22.73	17.66
			4	$9.0^{+1.01}_{-1.01}$	$-1.35^{+0.0}_{-0.0}$	4.55	2.63
STELIB	Inner	0.812	1	$8.0^{+1.1}_{-1.0}$	$-0.33^{+0.0}_{-0.12}$	90.91	92.31
			2	$4.0^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	7.69
	Outer	1.545	1	$7.0^{+1.08}_{-1.12}$	$-0.33^{+0.07}_{-0.1}$	59.94	45.64
			2	$3.0^{+1.02}_{-1.04}$	$0.35^{+0.02}_{-0.03}$	19.98	10.91
			3	$13.0^{+1.02}_{-1.04}$	$0.35^{+0.02}_{-0.03}$	19.98	43.45
			4	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.1	0.0
ELODIE	Inner	3.047	1	$6.0^{+1.03}_{-1.08}$	$-0.33^{+0.04}_{-0.01}$	45.45	24.05
			2	$13.0^{+1.03}_{-1.08}$	$0.35^{+0.04}_{-0.01}$	45.45	72.89
			3	$3.0^{+1.01}_{-1.01}$	$0.0^{+0.01}_{-0.0}$	9.09	3.05
	Outer	1.516	1	$3.0^{+1.13}_{-1.2}$	$-0.33^{+0.06}_{-0.02}$	45.45	18.47
			2	$13.0^{+1.08}_{-1.12}$	$0.35^{+0.04}_{-0.01}$	28.79	63.59
			3	$6.0^{+1.06}_{-1.09}$	$-0.33^{+0.03}_{-0.01}$	22.73	16.52
			4	$6.0^{+1.01}_{-1.01}$	$-2.25^{+0.0}_{-0.0}$	3.03	1.42
E-MaStar	Inner	0.002	1	$2.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	98.06
			2	$0.02^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	1.94
	Outer	0.013	1	$0.02^{+63.22}_{-1.0}$	$-0.33^{+0.03}_{-0.1}$	90.91	89.37
			2	$0.4^{+1.51}_{-1.0}$	$-1.0^{+0.0}_{-0.01}$	9.09	10.63
Th-MaStar	Inner	0.002	1	$2.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	98.06
			2	$0.02^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	1.94
	Outer	0.013	1	$0.02^{+63.22}_{-1.0}$	$-0.33^{+0.03}_{-0.1}$	90.91	89.37
			2	$0.4^{+1.51}_{-1.0}$	$-1.0^{+0.0}_{-0.01}$	9.09	10.63

Table E.7: Luminosity weighted stellar population properties of NGC 2911's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction		
MILES	Inner	0.945	1	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.0}_{-0.0}$	74.26	93.96		
			2	$3.0^{+1.01}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	25.74	6.04		
STELIB	Outer	1.284	1	$3.0^{+1.07}_{-1.12}$	$-0.33^{+0.03}_{-0.01}$	54.55	20.47		
			2	$11.0^{+1.06}_{-1.1}$	$0.35^{+0.02}_{-0.01}$	45.45	79.53		
	Inner	1.061	1	$3.0^{+1.03}_{-1.04}$	$0.35^{+0.0}_{-0.0}$	58.33	26.51		
			2	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.0}_{-0.0}$	41.67	73.49		
	Outer	1.316	1	$3.0^{+1.0}_{-1.27}$	$0.35^{+0.0}_{-0.02}$	90.91	71.61		
			2	$13.0^{+1.0}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	9.09	28.39		
ELODIE	Inner	0.732	1	$13.0^{+1.02}_{-1.02}$	$0.35^{+0.0}_{-0.01}$	72.73	97.23		
			2	$0.7^{+1.01}_{-1.01}$	$0.35^{+0.0}_{-0.0}$	27.27	2.77		
	Outer	1.254	1	$13.0^{+1.04}_{-1.05}$	$0.0^{+0.04}_{-0.06}$	40.0	46.57		
			2	$13.0^{+1.03}_{-1.04}$	$0.35^{+0.03}_{-0.05}$	33.33	50.5		
E-MaStar			3	$0.7^{+1.03}_{-1.03}$	$0.35^{+0.03}_{-0.04}$	26.67	2.93		
			Inner	0.001	1	$4.0^{+1.0}_{-1.49}$	$0.35^{+0.0}_{-0.0}$	50.0	33.59
					2	$8.0^{+1.0}_{-1.49}$	$0.2^{+0.0}_{-0.0}$	50.0	66.41
	Outer	0.015	1	$0.01^{+2.89}_{-3.12}$	$-0.7^{+0.07}_{-0.39}$	50.0	5.58		
			2	$0.5^{+2.89}_{-3.12}$	$0.2^{+0.07}_{-0.39}$	50.0	94.42		
	Th-MaStar	Inner	0.001	1	$4.0^{+1.0}_{-1.49}$	$0.35^{+0.0}_{-0.0}$	50.0	33.59	
2				$8.0^{+1.0}_{-1.49}$	$0.2^{+0.0}_{-0.0}$	50.0	66.41		
Outer		0.015	1	$0.01^{+2.89}_{-3.12}$	$-0.7^{+0.07}_{-0.39}$	50.0	5.58		
			2	$0.5^{+2.89}_{-3.12}$	$0.2^{+0.07}_{-0.39}$	50.0	94.42		

Table E.8: Luminosity weighted stellar population properties of NGC 3078's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction	
MILES	Inner	0.951	1	$12.0^{+1.06}_{-1.03}$	$-0.33^{+0.0}_{-0.06}$	46.2	59.41	
			2	$3.0^{+1.03}_{-1.02}$	$0.35^{+0.0}_{-0.03}$	26.4	14.65	
			3	$9.0^{+1.03}_{-1.02}$	$-0.33^{+0.0}_{-0.03}$	26.4	25.94	
			4	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.0	
	Outer	0.232	1	$13.0^{+1.0}_{-1.03}$	$-0.33^{+0.03}_{-0.01}$	49.95	70.86	
			2	$9.0^{+1.0}_{-1.02}$	$-0.33^{+0.02}_{-0.0}$	24.98	25.26	
			3	$0.7^{+1.0}_{-1.02}$	$0.35^{+0.02}_{-0.0}$	24.98	3.88	
			4	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.1	0.0	
STELIB	Inner	1.023	1	$13.0^{+1.01}_{-1.05}$	$-0.33^{+0.0}_{-0.02}$	45.45	42.23	
			2	$12.0^{+1.01}_{-1.05}$	$0.0^{+0.0}_{-0.02}$	45.45	48.31	
			3	$7.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	4.55	2.42	
			4	$13.0^{+1.0}_{-1.01}$	$0.35^{+0.0}_{-0.0}$	4.55	7.04	
	Outer	0.216	1	$13.0^{+1.02}_{-1.03}$	$-0.33^{+0.04}_{-0.0}$	90.91	93.34	
			2	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	6.66	
	ELODIE	Inner	3.162	1	$10.0^{+1.12}_{-1.33}$	$-0.33^{+0.06}_{-0.09}$	60.61	75.0
				2	$3.0^{+1.06}_{-1.15}$	$0.35^{+0.03}_{-0.04}$	30.3	19.05
3				$4.0^{+1.02}_{-1.04}$	$0.0^{+0.01}_{-0.01}$	9.09	5.95	
Outer		0.408	1	$10.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	90.91	83.31	
	2		$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	9.09	16.69		
E-MaStar	Inner	0.002	1	$1.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	90.91	99.55	
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.45	
	Outer	0.002	1	$0.01^{+1.48}_{-1.0}$	$-0.7^{+0.0}_{-0.08}$	50.0	1.54	
			2	$5.0^{+1.48}_{-1.0}$	$-1.0^{+0.0}_{-0.08}$	50.0	98.46	
Th-MaStar	Inner	0.002	1	$1.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	90.91	99.55	
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.45	
	Outer	0.002	1	$0.01^{+1.48}_{-1.0}$	$-0.7^{+0.0}_{-0.08}$	50.0	1.54	
			2	$5.0^{+1.48}_{-1.0}$	$-1.0^{+0.0}_{-0.08}$	50.0	98.46	

Table E.9: Luminosity weighted stellar population properties of NGC 3325's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.539	1	$12.0^{+1.02}_{-1.06}$	$-0.33^{+0.04}_{-0.02}$	41.67	43.75
			2	$11.0^{+1.01}_{-1.03}$	$-0.33^{+0.02}_{-0.01}$	25.0	24.25
			3	$8.0^{+1.01}_{-1.02}$	$-0.33^{+0.01}_{-0.01}$	16.67	12.17
			4	$11.0^{+1.01}_{-1.02}$	$0.0^{+0.01}_{-0.01}$	16.67	19.83
	Outer	0.271	1	$9.0^{+1.12}_{-1.0}$	$-0.33^{+0.0}_{-0.08}$	90.91	98.8
			2	$0.6^{+1.01}_{-1.0}$	$0.0^{+0.0}_{-0.01}$	9.09	1.2
			1	$3.0^{+1.11}_{-1.03}$	$0.35^{+0.03}_{-0.06}$	33.33	37.7
			2	$5.0^{+1.08}_{-1.02}$	$0.0^{+0.02}_{-0.04}$	25.0	34.36
STELIB	Inner	0.664	3	$0.7^{+1.05}_{-1.01}$	$0.35^{+0.01}_{-0.03}$	16.67	5.22
			4	$7.0^{+1.04}_{-1.01}$	$-0.33^{+0.01}_{-0.02}$	12.5	19.72
			5	$0.5^{+1.04}_{-1.01}$	$0.35^{+0.01}_{-0.02}$	12.5	3.0
	Outer	0.391	1	$5.0^{+1.09}_{-1.23}$	$0.0^{+0.08}_{-0.0}$	66.01	90.7
			2	$0.6^{+1.04}_{-1.11}$	$0.35^{+0.04}_{-0.0}$	33.0	9.2
			3	$0.2^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.1
	Inner	0.566	1	$6.0^{+1.02}_{-1.05}$	$-0.33^{+0.04}_{-0.02}$	33.0	20.45
			2	$12.0^{+1.02}_{-1.05}$	$-0.33^{+0.04}_{-0.02}$	33.0	37.05
			3	$11.0^{+1.02}_{-1.05}$	$0.0^{+0.04}_{-0.02}$	33.0	41.83
			4	$13.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.68
	Outer	0.312	1	$4.0^{+1.46}_{-1.02}$	$-0.33^{+0.0}_{-0.11}$	90.91	90.03
			2	$3.0^{+1.04}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	9.97
E-MaStar	Inner	0.003	1	$1.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	90.91	99.52
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.48
	Outer	0.003	1	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	50.0	6.94
			2	$0.5^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	93.06
Th-MaStar	Inner	0.003	1	$1.0^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	90.91	99.52
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.48
	Outer	0.003	1	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	50.0	6.94
			2	$0.5^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	93.06

Table E.10: Luminosity weighted stellar population properties of NGC 3923's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.443	1	$12.0^{+1.03}_{-1.06}$	$-0.33^{+0.05}_{-0.04}$	74.26	69.08
			2	$10.0^{+1.01}_{-1.02}$	$0.35^{+0.02}_{-0.01}$	24.75	30.83
			3	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.09
	Outer	1.02	1	$8.0^{+1.02}_{-1.11}$	$-0.33^{+0.04}_{-0.01}$	66.01	48.34
			2	$11.0^{+1.01}_{-1.06}$	$0.35^{+0.02}_{-0.01}$	33.0	51.63
			3	$0.1^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.03
STELIB	Inner	0.444	1	$13.0^{+1.02}_{-1.06}$	$0.35^{+0.04}_{-0.02}$	50.0	75.87
			2	$7.0^{+1.01}_{-1.03}$	$-0.33^{+0.02}_{-0.01}$	25.0	12.88
			3	$5.0^{+1.01}_{-1.03}$	$0.0^{+0.02}_{-0.01}$	25.0	11.25
			4	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.01}_{-0.02}$	16.67	31.84
	Outer	1.057	1	$7.0^{+1.05}_{-1.09}$	$-0.33^{+0.03}_{-0.05}$	50.0	32.31
			2	$12.0^{+1.02}_{-1.03}$	$0.0^{+0.01}_{-0.02}$	16.67	21.5
			3	$6.0^{+1.02}_{-1.03}$	$0.35^{+0.01}_{-0.02}$	16.67	14.35
			4	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.01}_{-0.02}$	16.67	31.84
ELODIE	Inner	0.961	1	$13.0^{+1.06}_{-1.1}$	$-0.33^{+0.03}_{-0.08}$	50.0	61.18
			2	$11.0^{+1.03}_{-1.05}$	$-0.33^{+0.01}_{-0.04}$	25.0	26.43
			3	$3.0^{+1.03}_{-1.05}$	$0.35^{+0.01}_{-0.04}$	25.0	12.38
			4	$0.6^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.09
	Outer	1.206	1	$12.0^{+1.06}_{-1.08}$	$0.35^{+0.02}_{-0.02}$	49.5	66.61
			2	$5.0^{+1.03}_{-1.04}$	$-0.33^{+0.01}_{-0.01}$	24.75	9.9
			3	$11.0^{+1.03}_{-1.04}$	$0.0^{+0.01}_{-0.01}$	24.75	23.4
			4	$0.6^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.09
E-MaStar	Inner	0.001	1	$6.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.92
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.08
	Outer	0.004	1	$8.0^{+1.11}_{-1.0}$	$0.0^{+0.0}_{-0.27}$	90.91	99.94
			2	$0.01^{+1.01}_{-1.0}$	$-0.7^{+0.0}_{-0.03}$	9.09	0.06
Th-MaStar	Inner	0.001	1	$6.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.92
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.08
	Outer	0.004	1	$8.0^{+1.11}_{-1.0}$	$0.0^{+0.0}_{-0.27}$	90.91	99.94
			2	$0.01^{+1.01}_{-1.0}$	$-0.7^{+0.0}_{-0.03}$	9.09	0.06

Table E.11: Luminosity weighted stellar population properties of NGC 4697's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.663	1	$11.0^{+1.02}_{-1.02}$	$-0.33^{+0.03}_{-0.02}$	33.3	29.51
			2	$13.0^{+1.02}_{-1.02}$	$-0.33^{+0.03}_{-0.02}$	33.3	34.36
			3	$11.0^{+1.02}_{-1.02}$	$0.0^{+0.03}_{-0.02}$	33.3	36.13
			4	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.1	0.0
	Outer	0.387	1	$9.0^{+1.01}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	49.5	43.51
			2	$12.0^{+1.01}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	49.5	56.4
			3	$0.4^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.08
STELIB	Inner	0.841	1	$9.0^{+1.01}_{-1.04}$	$-0.33^{+0.08}_{-0.0}$	45.45	32.99
			2	$13.0^{+1.01}_{-1.04}$	$0.0^{+0.08}_{-0.0}$	45.45	57.76
			3	$13.0^{+1.0}_{-1.01}$	$-0.33^{+0.02}_{-0.0}$	9.09	9.25
	Outer	0.496	1	$9.0^{+1.08}_{-1.07}$	$-0.33^{+0.09}_{-0.03}$	72.73	88.13
			2	$1.5^{+1.02}_{-1.02}$	$0.0^{+0.03}_{-0.01}$	22.73	6.9
			3	$8.0^{+1.0}_{-1.0}$	$-0.33^{+0.01}_{-0.0}$	4.55	4.97
			4	$11.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.59
ELODIE	Inner	1.004	1	$12.0^{+1.01}_{-1.05}$	$-0.33^{+0.04}_{-0.01}$	49.5	52.04
			2	$3.0^{+1.01}_{-1.03}$	$0.0^{+0.02}_{-0.0}$	24.75	9.18
			3	$11.0^{+1.01}_{-1.03}$	$0.35^{+0.02}_{-0.0}$	24.75	38.19
			4	$11.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.59
	Outer	0.504	1	$3.0^{+1.22}_{-1.06}$	$-0.33^{+0.04}_{-0.21}$	74.26	34.73
			2	$13.0^{+1.07}_{-1.02}$	$0.35^{+0.01}_{-0.07}$	24.75	65.26
			3	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.01
E-MaStar	Inner	0.001	1	$2.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.86
			2	$0.01^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	9.09	0.14
	Outer	0.002	1	$5.0^{+1.19}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	42.48
			2	$12.0^{+1.19}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	50.0	57.52
Th-MaStar	Inner	0.001	1	$2.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.86
			2	$0.01^{+1.0}_{-1.0}$	$0.2^{+0.0}_{-0.0}$	9.09	0.14
	Outer	0.002	1	$5.0^{+1.19}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	50.0	42.48
			2	$12.0^{+1.19}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	50.0	57.52

Table E.12: Luminosity weighted stellar population properties of NGC 5044’s inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.631	1	$9.0^{+1.07}_{-1.05}$	$-0.33^{+0.02}_{-0.04}$	61.36	50.8
			2	$9.0^{+1.04}_{-1.03}$	$0.35^{+0.01}_{-0.02}$	38.64	49.2
STELIB	Outer	0.287	1	$13.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	99.09
			2	$0.8^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.91
	Inner	0.625	1	$7.0^{+1.01}_{-1.02}$	$-0.33^{+0.02}_{-0.0}$	30.3	17.25
			2	$10.0^{+1.01}_{-1.02}$	$-0.33^{+0.02}_{-0.0}$	30.3	23.76
			3	$13.0^{+1.01}_{-1.02}$	$0.35^{+0.02}_{-0.0}$	30.3	50.47
			4	$8.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	4.55	2.89
			5	$13.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	4.55	5.64
	Outer	0.353	1	$13.0^{+1.03}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	39.39	36.48
			2	$7.0^{+1.02}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	30.3	16.21
			3	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.01}_{-0.0}$	30.3	47.32
ELODIE	Inner	0.559	1	$13.0^{+1.0}_{-1.06}$	$0.35^{+0.02}_{-0.03}$	69.58	82.94
			2	$11.0^{+1.0}_{-1.02}$	$-2.25^{+0.01}_{-0.01}$	20.42	7.9
			3	$13.0^{+1.0}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	10.0	9.16
	Outer	0.309	1	$13.0^{+1.0}_{-1.08}$	$-0.33^{+0.02}_{-0.0}$	99.01	99.66
			2	$6.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.34
E-MaStar	Inner	0.004	1	$1.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	90.91	99.67
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.33
	Outer	0.003	1	$8.0^{+1.15}_{-1.0}$	$0.0^{+0.02}_{-0.28}$	90.91	99.96
			2	$0.01^{+1.01}_{-1.0}$	$-0.33^{+0.0}_{-0.03}$	9.09	0.04
Th-MaStar	Inner	0.004	1	$1.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	90.91	99.67
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.33
	Outer	0.003	1	$8.0^{+1.15}_{-1.0}$	$0.0^{+0.02}_{-0.28}$	90.91	99.96
			2	$0.01^{+1.01}_{-1.0}$	$-0.33^{+0.0}_{-0.03}$	9.09	0.04

Table E.13: Luminosity weighted stellar population properties of NGC 5061's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction			
MILES	Inner	1.518	1	$12.0^{+1.03}_{-1.05}$	$-0.33^{+0.03}_{-0.04}$	33.33	35.81			
			2	$3.0^{+1.02}_{-1.02}$	$-0.33^{+0.01}_{-0.02}$	16.67	5.65			
			3	$1.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.02}$	16.67	3.04			
			4	$10.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.02}$	16.67	23.9			
			5	$13.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.02}$	16.67	31.6			
	Outer	0.254	1	$3.0^{+1.03}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	49.5	22.53			
			2	$13.0^{+1.03}_{-1.03}$	$-0.33^{+0.01}_{-0.0}$	49.5	77.46			
			3	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.01			
			STELIB	Inner	2.007	1	$10.0^{+1.02}_{-1.03}$	$-0.33^{+0.02}_{-0.02}$	37.13	53.03
						2	$4.0^{+1.02}_{-1.03}$	$0.0^{+0.02}_{-0.02}$	37.13	28.01
3	$3.0^{+1.02}_{-1.02}$	$0.35^{+0.02}_{-0.01}$				24.75	18.76			
4	$0.6^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$				0.99	0.19			
Outer	0.309	1		$6.0^{+1.1}_{-1.06}$	$-0.33^{+0.0}_{-0.01}$	59.41	76.24			
		2		$3.0^{+1.03}_{-1.02}$	$-0.33^{+0.0}_{-0.0}$	19.8	14.27			
		3		$0.6^{+1.03}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	19.8	5.26			
		4		$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	4.23			
Inner	1.504	1		$4.0^{+1.18}_{-1.06}$	$0.0^{+0.02}_{-0.02}$	74.26	56.25			
		2		$8.0^{+1.06}_{-1.02}$	$0.35^{+0.01}_{-0.01}$	24.75	43.59			
		3	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.16				
Outer	0.294	1	$11.0^{+1.08}_{-1.0}$	$-0.33^{+0.0}_{-0.08}$	90.91	98.63				
		2	$0.7^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	1.37				
E-MaStar	Inner	0.003	1	$1.0^{+1.09}_{-1.0}$	$0.2^{+0.03}_{-0.0}$	90.91	99.64			
			2	$0.01^{+1.01}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.36			
	Outer	0.001	1	$1.0^{+1.25}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	50.0	22.22			
			2	$8.0^{+1.25}_{-1.0}$	$-0.7^{+0.0}_{-0.01}$	50.0	77.78			
Th-MaStar	Inner	0.003	1	$1.0^{+1.09}_{-1.0}$	$0.2^{+0.03}_{-0.0}$	90.91	99.64			
			2	$0.01^{+1.01}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.36			
	Outer	0.001	1	$1.0^{+1.25}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	50.0	22.22			
			2	$8.0^{+1.25}_{-1.0}$	$-0.7^{+0.0}_{-0.01}$	50.0	77.78			

Table E.14: Luminosity weighted stellar population properties of NGC 5084's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	1.453	1	$11.0^{+1.03}_{-1.02}$	$0.35^{+0.0}_{-0.0}$	66.67	89.58
			2	$3.0^{+1.01}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	30.3	8.84
			3	$6.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	3.03	1.57
STELIB	Outer	0.453	1	$9.0^{+1.02}_{-1.05}$	$-0.33^{+0.05}_{-0.01}$	74.24	58.75
			2	$12.0^{+1.01}_{-1.02}$	$0.35^{+0.02}_{-0.0}$	25.76	41.25
	Inner	1.541	1	$10.0^{+1.08}_{-1.05}$	$0.35^{+0.05}_{-0.06}$	50.0	71.28
			2	$7.0^{+1.04}_{-1.03}$	$-0.33^{+0.02}_{-0.03}$	25.0	16.69
			3	$3.0^{+1.04}_{-1.03}$	$0.35^{+0.02}_{-0.03}$	25.0	12.03
	Outer	0.452	1	$7.0^{+1.04}_{-1.05}$	$-0.33^{+0.01}_{-0.0}$	51.52	37.41
2			$13.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.0}$	25.76	52.21	
3			$4.0^{+1.02}_{-1.02}$	$-0.33^{+0.01}_{-0.0}$	22.73	10.39	
ELODIE	Inner	0.473	1	$7.0^{+1.05}_{-1.04}$	$0.35^{+0.02}_{-0.02}$	56.58	58.11
			2	$7.0^{+1.01}_{-1.01}$	$0.0^{+0.01}_{-0.0}$	14.14	11.32
			3	$13.0^{+1.01}_{-1.01}$	$0.0^{+0.01}_{-0.0}$	14.14	21.21
			4	$12.0^{+1.01}_{-1.01}$	$-2.25^{+0.01}_{-0.0}$	14.14	9.24
			5	$0.6^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.12
	Outer	0.604	1	$13.0^{+1.01}_{-1.02}$	$0.0^{+0.01}_{-0.0}$	79.21	98.73
			2	$0.3^{+1.0}_{-1.01}$	$0.35^{+0.0}_{-0.0}$	19.8	1.27
			3	$0.01^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	0.0
			E-MaStar	Inner	0.002	1	$2.0^{+2.28}_{-1.1}$
2	$0.01^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.0}$				0.99	0.01
Outer	0.001	1		$5.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	92.96
		2		$9.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	9.09	7.04
Th-MaStar	Inner	0.002	1	$2.0^{+2.28}_{-1.1}$	$0.0^{+0.02}_{-0.03}$	99.01	99.99
			2	$0.01^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.01
	Outer	0.001	1	$5.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	92.96
			2	$9.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	9.09	7.04

Table E.15: Luminosity weighted stellar population properties of NGC 5152's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.39	1	$13.0^{+1.01}_{-1.03}$	$0.35^{+0.01}_{-0.0}$	58.33	67.71
			2	$12.0^{+1.0}_{-1.01}$	$0.0^{+0.0}_{-0.0}$	25.0	20.49
			3	$13.0^{+1.0}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	16.67	11.8
	Outer	0.594	1	$3.0^{+1.14}_{-1.1}$	$-0.33^{+0.03}_{-0.09}$	33.0	18.69
			2	$9.0^{+1.14}_{-1.1}$	$-0.33^{+0.03}_{-0.09}$	33.0	46.68
			3	$4.0^{+1.14}_{-1.1}$	$0.35^{+0.03}_{-0.09}$	33.0	34.46
			4	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.17
STELIB	Inner	0.443	1	$13.0^{+1.04}_{-1.04}$	$0.35^{+0.01}_{-0.01}$	65.15	80.83
			2	$9.0^{+1.02}_{-1.02}$	$-0.33^{+0.0}_{-0.0}$	30.3	15.99
			3	$10.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	4.55	3.18
	Outer	0.612	1	$7.0^{+1.04}_{-1.06}$	$-0.33^{+0.04}_{-0.09}$	66.01	40.66
			2	$13.0^{+1.02}_{-1.03}$	$0.35^{+0.02}_{-0.05}$	33.0	59.3
			3	$0.2^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.04
			4	$11.0^{+1.03}_{-1.02}$	$0.0^{+0.0}_{-0.01}$	33.0	41.18
ELODIE	Inner	0.446	2	$5.0^{+1.03}_{-1.02}$	$0.35^{+0.0}_{-0.01}$	33.0	24.94
			3	$7.0^{+1.03}_{-1.02}$	$0.35^{+0.0}_{-0.01}$	33.0	33.78
			4	$0.5^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.11
	Outer	0.63	1	$10.0^{+1.03}_{-1.04}$	$-0.33^{+0.01}_{-0.01}$	33.0	22.94
			2	$11.0^{+1.03}_{-1.04}$	$0.0^{+0.01}_{-0.01}$	33.0	30.1
			3	$13.0^{+1.03}_{-1.04}$	$0.35^{+0.01}_{-0.01}$	33.0	46.85
			4	$0.7^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	0.1
E-MaStar	Inner	0.001	1	$13.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.63
			2	$0.03^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.37
	Outer	0.004	1	$8.0^{+1.0}_{-1.0}$	$-0.33^{+0.08}_{-0.0}$	90.91	99.71
			2	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.01}_{-0.0}$	9.09	0.29
Th-MaStar	Inner	0.001	1	$13.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	90.91	99.63
			2	$0.03^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.37
	Outer	0.004	1	$8.0^{+1.0}_{-1.0}$	$-0.33^{+0.08}_{-0.0}$	90.91	99.71
			2	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.01}_{-0.0}$	9.09	0.29

Table E.16: Luminosity weighted stellar population properties of NGC 5153's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.314	1	$11.0^{+1.03}_{-1.03}$	$0.0^{+0.02}_{-0.03}$	34.85	34.35
			2	$8.0^{+1.03}_{-1.02}$	$-0.33^{+0.01}_{-0.03}$	30.3	18.54
			3	$12.0^{+1.03}_{-1.02}$	$0.35^{+0.01}_{-0.03}$	30.3	42.86
			4	$13.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	4.55	4.25
	Outer	0.963	1	$9.0^{+1.05}_{-1.17}$	$-0.33^{+0.13}_{-0.04}$	66.01	57.15
			2	$11.0^{+1.02}_{-1.08}$	$0.0^{+0.06}_{-0.02}$	33.0	42.07
			3	$8.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	0.78
			4	$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	2.48
STELIB	Inner	0.354	1	$5.0^{+1.07}_{-1.03}$	$0.0^{+0.12}_{-0.02}$	66.01	49.0
			2	$13.0^{+1.03}_{-1.02}$	$-0.33^{+0.06}_{-0.01}$	33.0	48.52
			3	$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.99	2.48
			4	$13.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.03}$	16.67	32.23
	Outer	0.971	1	$7.0^{+1.03}_{-1.04}$	$-0.33^{+0.02}_{-0.07}$	33.33	21.76
			2	$13.0^{+1.03}_{-1.04}$	$-0.33^{+0.02}_{-0.07}$	33.33	38.21
			3	$3.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.03}$	16.67	7.8
			4	$13.0^{+1.02}_{-1.02}$	$0.35^{+0.01}_{-0.03}$	16.67	32.23
ELODIE	Inner	0.505	1	$4.0^{+1.1}_{-1.19}$	$-0.33^{+0.04}_{-0.09}$	74.26	40.04
			2	$13.0^{+1.03}_{-1.06}$	$0.35^{+0.01}_{-0.03}$	24.75	59.31
			3	$9.0^{+1.0}_{-1.0}$	$-2.25^{+0.0}_{-0.0}$	0.99	0.66
	Outer	1.009	1	$13.0^{+1.04}_{-1.09}$	$-0.33^{+0.09}_{-0.04}$	50.0	48.74
			2	$11.0^{+1.04}_{-1.09}$	$0.0^{+0.09}_{-0.04}$	50.0	51.26
			3	$11.0^{+1.0}_{-1.07}$	$-0.33^{+0.0}_{-0.02}$	50.0	42.91
E-MaStar	Inner	0.002	1	$10.0^{+1.0}_{-1.07}$	$0.2^{+0.0}_{-0.02}$	50.0	57.09
			2	$11.0^{+1.0}_{-1.07}$	$-0.33^{+0.0}_{-0.02}$	50.0	42.91
	Outer	0.007	1	$13.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	90.91	99.89
			2	$0.01^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.11
Th-MaStar	Inner	0.002	1	$10.0^{+1.0}_{-1.07}$	$0.2^{+0.0}_{-0.02}$	50.0	57.09
			2	$11.0^{+1.0}_{-1.07}$	$-0.33^{+0.0}_{-0.02}$	50.0	42.91
	Outer	0.007	1	$13.0^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	90.91	99.89
			2	$0.01^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	9.09	0.11

Table E.17: Luminosity weighted stellar population properties of NGC 5903's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.287	1	$9.0^{+1.03}_{-1.01}$	$-0.33^{+0.0}_{-0.04}$	25.0	18.35
			2	$12.0^{+1.03}_{-1.01}$	$-0.33^{+0.0}_{-0.04}$	25.0	23.94
			3	$12.0^{+1.03}_{-1.01}$	$0.0^{+0.0}_{-0.04}$	25.0	29.57
			4	$9.0^{+1.03}_{-1.01}$	$0.35^{+0.0}_{-0.04}$	25.0	28.14
	Outer	0.551	1	$3.0^{+1.13}_{-1.12}$	$-0.33^{+0.09}_{-0.05}$	50.0	29.09
			2	$9.0^{+1.06}_{-1.06}$	$-0.33^{+0.05}_{-0.03}$	25.0	36.84
			3	$7.0^{+1.06}_{-1.06}$	$0.0^{+0.05}_{-0.03}$	25.0	34.07
STELIB	Inner	0.376	1	$13.0^{+1.01}_{-1.05}$	$0.35^{+0.0}_{-0.01}$	50.0	72.14
			2	$8.0^{+1.01}_{-1.04}$	$-0.33^{+0.0}_{-0.01}$	45.45	25.07
			3	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	4.55	2.79
	Outer	0.566	1	$7.0^{+1.02}_{-1.21}$	$-0.33^{+0.13}_{-0.0}$	99.9	99.93
			2	$3.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	0.1	0.07
			3	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	78.72
ELODIE	Inner	0.961	2	$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	9.09	21.28
			3	$6.0^{+1.01}_{-1.06}$	$-0.33^{+0.02}_{-0.0}$	24.75	14.75
	Outer	0.57	1	$10.0^{+1.03}_{-1.12}$	$0.35^{+0.04}_{-0.01}$	49.5	69.81
			2	$11.0^{+1.01}_{-1.06}$	$-2.25^{+0.02}_{-0.0}$	25.74	15.44
			3	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	99.94
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.06
E-MaStar	Inner	0.002	1	$11.0^{+1.09}_{-1.51}$	$-0.33^{+0.14}_{-0.0}$	90.91	99.94
			2	$0.01^{+1.01}_{-1.04}$	$-0.7^{+0.01}_{-0.0}$	9.09	0.06
	Outer	0.003	1	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	99.94
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.06
Th-MaStar	Inner	0.002	1	$11.0^{+1.09}_{-1.51}$	$-0.33^{+0.14}_{-0.0}$	90.91	99.94
			2	$0.01^{+1.01}_{-1.04}$	$-0.7^{+0.01}_{-0.0}$	9.09	0.06
	Outer	0.003	1	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	90.91	99.94
			2	$0.01^{+1.0}_{-1.0}$	$-0.7^{+0.0}_{-0.0}$	9.09	0.06

Table E.18: Luminosity weighted stellar population properties of NGC 7252's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction	
MILES	Inner	0.756	1	$0.5^{+1.06}_{-1.05}$	$-0.33^{+0.03}_{-0.01}$	21.21	12.35	
			2	$0.6^{+1.06}_{-1.05}$	$-0.33^{+0.03}_{-0.01}$	21.21	14.58	
			3	$0.9^{+1.06}_{-1.05}$	$0.0^{+0.03}_{-0.01}$	21.21	22.48	
			4	$3.0^{+1.05}_{-1.04}$	$-1.35^{+0.03}_{-0.01}$	18.94	34.26	
			5	$0.8^{+1.04}_{-1.03}$	$0.0^{+0.02}_{-0.01}$	15.15	14.55	
			6	$0.5^{+1.01}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	2.27	1.78	
	Outer	0.209	1	$13.0^{+1.07}_{-1.1}$	$-1.35^{+0.01}_{-0.03}$	25.0	47.14	
			2	$0.6^{+1.07}_{-1.1}$	$0.0^{+0.01}_{-0.03}$	25.0	6.43	
			3	$6.0^{+1.05}_{-1.07}$	$-1.35^{+0.01}_{-0.02}$	16.67	17.41	
			4	$6.0^{+1.05}_{-1.07}$	$-0.33^{+0.01}_{-0.02}$	16.67	25.28	
STELIB	Inner	1.095	5	$0.5^{+1.05}_{-1.07}$	$0.0^{+0.01}_{-0.02}$	16.67	3.73	
			1	$0.6^{+1.13}_{-1.0}$	$0.0^{+0.01}_{-0.02}$	79.21	88.8	
			2	$0.2^{+1.03}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	19.8	9.57	
			3	$1.0^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	0.99	1.63	
	Outer	0.364	1	$0.03^{+1.0}_{-1.0}$	$0.0^{+0.01}_{-0.03}$	45.45	12.22	
			2	$0.4^{+1.0}_{-1.0}$	$0.35^{+0.01}_{-0.03}$	45.45	81.02	
			3	$0.3^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	4.55	5.3	
			4	$0.04^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	4.55	1.46	
	ELODIE	Inner	1.746	1	$0.01^{+1.0}_{-2.01}$	$0.0^{+0.02}_{-0.0}$	45.45	2.15
				2	$0.3^{+1.0}_{-1.42}$	$0.0^{+0.01}_{-0.0}$	22.73	21.08
3				$0.4^{+1.0}_{-1.42}$	$0.0^{+0.01}_{-0.0}$	22.73	25.77	
4				$6.0^{+1.0}_{-1.15}$	$-2.25^{+0.0}_{-0.0}$	9.09	51.01	
Outer		0.28	1	$10.0^{+1.09}_{-1.13}$	$-2.25^{+0.07}_{-0.0}$	68.18	80.69	
			2	$0.7^{+1.03}_{-1.04}$	$0.35^{+0.02}_{-0.0}$	22.73	6.48	
			3	$13.0^{+1.01}_{-1.02}$	$-2.25^{+0.01}_{-0.0}$	9.09	12.84	
			E-MaStar	Inner	0.001	1	$0.01^{+2.64}_{-1.0}$	$0.0^{+0.23}_{-0.01}$
2		$0.8^{+1.1}_{-1.0}$				$-1.35^{+0.02}_{-0.0}$	9.09	79.12
Th-MaStar		Outer	0.001	1	$0.4^{+3.92}_{-1.0}$	$-1.0^{+0.7}_{-0.0}$	90.91	99.32
	2			$0.01^{+1.15}_{-1.0}$	$-0.33^{+0.07}_{-0.0}$	9.09	0.68	
	Inner	0.001	1	$0.01^{+2.64}_{-1.0}$	$0.0^{+0.23}_{-0.01}$	90.91	20.88	
			2	$0.8^{+1.1}_{-1.0}$	$-1.35^{+0.02}_{-0.0}$	9.09	79.12	
Outer	0.001	1	$0.4^{+3.92}_{-1.0}$	$-1.0^{+0.7}_{-0.0}$	90.91	99.32		
		2	$0.01^{+1.15}_{-1.0}$	$-0.33^{+0.07}_{-0.0}$	9.09	0.68		

Table E.19: Luminosity weighted stellar population properties of NGC 7377's inner and outer region measured with FIREFLY, assuming a Salpeter IMF.. The χ^2_ν statistic of each FIREFLY fit is shown.

Stellar Library	Region	χ^2_ν	Component	Age (Gyr)	Metallicity (dex)	Luminosity fraction	Mass fraction
MILES	Inner	0.135	1	$11.0^{+1.02}_{-1.01}$	$-0.33^{+0.0}_{-0.0}$	90.91	93.94
			2	$11.0^{+1.0}_{-1.0}$	$-1.35^{+0.0}_{-0.0}$	9.09	6.06
	Outer	0.152	1	$12.0^{+1.07}_{-1.11}$	$-0.33^{+0.16}_{-0.01}$	60.61	71.17
			2	$9.0^{+1.04}_{-1.05}$	$-1.35^{+0.08}_{-0.0}$	30.3	18.95
			3	$11.0^{+1.01}_{-1.02}$	$-0.33^{+0.02}_{-0.0}$	9.09	9.88
STELIB	Inner	0.19	1	$1.0^{+1.03}_{-1.02}$	$-0.33^{+0.0}_{-0.03}$	30.3	5.39
			2	$8.0^{+1.03}_{-1.02}$	$-0.33^{+0.0}_{-0.03}$	30.3	35.72
			3	$10.0^{+1.03}_{-1.02}$	$-0.33^{+0.0}_{-0.03}$	30.3	43.91
			4	$0.9^{+1.0}_{-1.0}$	$0.0^{+0.0}_{-0.0}$	4.55	0.97
			5	$13.0^{+1.0}_{-1.0}$	$0.35^{+0.0}_{-0.0}$	4.55	14.01
	Outer	0.168	1	$2.0^{+1.01}_{-1.11}$	$-0.33^{+0.04}_{-0.03}$	25.0	10.02
			2	$7.0^{+1.01}_{-1.11}$	$-0.33^{+0.04}_{-0.03}$	25.0	30.22
			3	$13.0^{+1.01}_{-1.11}$	$-0.33^{+0.04}_{-0.03}$	25.0	52.96
			4	$1.0^{+1.01}_{-1.11}$	$0.0^{+0.04}_{-0.03}$	25.0	6.81
ELODIE	Inner	0.206	1	$5.0^{+1.09}_{-1.04}$	$-0.33^{+0.04}_{-0.0}$	99.01	98.42
			2	$9.0^{+1.0}_{-1.0}$	$-0.33^{+0.0}_{-0.0}$	0.99	1.58
	Outer	0.189	1	$11.0^{+1.03}_{-1.45}$	$-2.25^{+0.06}_{-0.06}$	60.61	35.8
			2	$13.0^{+1.02}_{-1.2}$	$0.35^{+0.03}_{-0.03}$	30.3	56.71
			3	$0.3^{+1.0}_{-1.03}$	$0.35^{+0.0}_{-0.0}$	4.55	0.33
			4	$11.0^{+1.0}_{-1.03}$	$0.35^{+0.0}_{-0.0}$	4.55	7.16
E-MaStar	Inner	0.001	1	$6.0^{+1.27}_{-1.0}$	$-0.7^{+0.0}_{-0.07}$	90.91	93.69
			2	$2.0^{+1.02}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	6.31
	Outer	0.003	1	$8.0^{+1.63}_{-1.28}$	$-0.7^{+0.25}_{-0.32}$	90.91	95.48
			2	$3.0^{+1.05}_{-1.03}$	$-0.7^{+0.02}_{-0.03}$	9.09	4.52
Th-MaStar	Inner	0.001	1	$6.0^{+1.27}_{-1.0}$	$-0.7^{+0.0}_{-0.07}$	90.91	93.69
			2	$2.0^{+1.02}_{-1.0}$	$0.35^{+0.0}_{-0.01}$	9.09	6.31
	Outer	0.003	1	$8.0^{+1.63}_{-1.28}$	$-0.7^{+0.25}_{-0.32}$	90.91	95.48
			2	$3.0^{+1.05}_{-1.03}$	$-0.7^{+0.02}_{-0.03}$	9.09	4.52

Appendix F

Spatially-resolved Stellar Kinematics of J1153

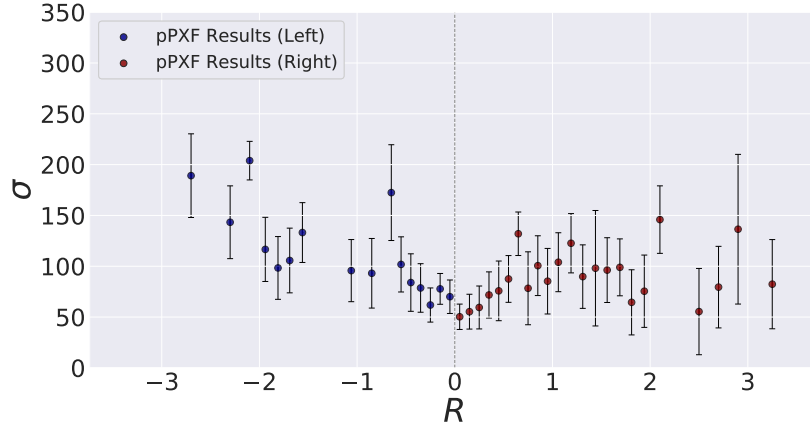


Figure F.1: Stellar velocity dispersion profile for J1153's major axis (low resolution).

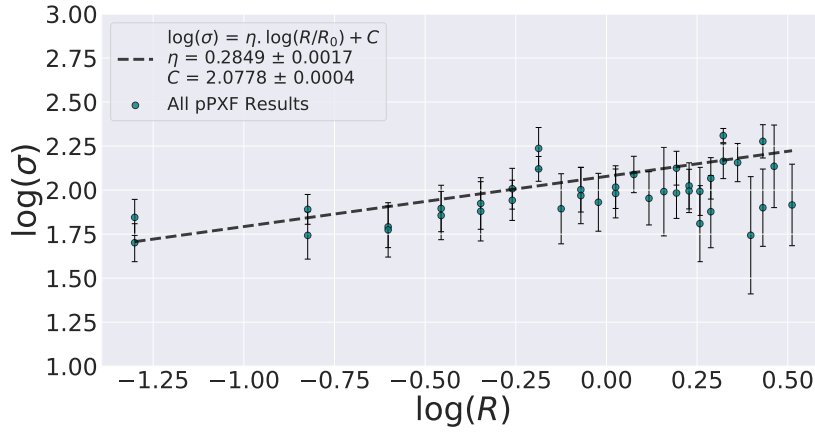


Figure F.2: Stellar velocity dispersion slope for J1153's major axis (low resolution). The slope is positive. The profile can be interpreted as increasing with reasonable certainty.

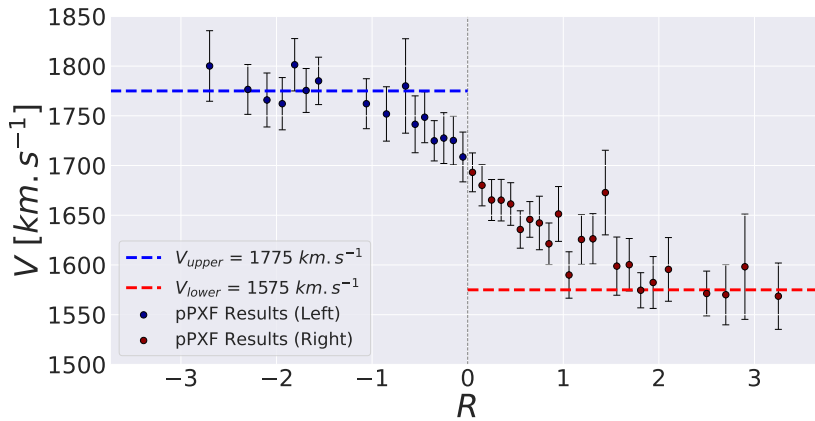


Figure F.3: Rotational velocity profile of J1153's major axis (low resolution). The pPXF results show that J1153 has strong rotation along its major axis with $V_{max} = (V_{upper} - V_{lower})/2 \approx 100 \text{ km.s}^{-1}$.

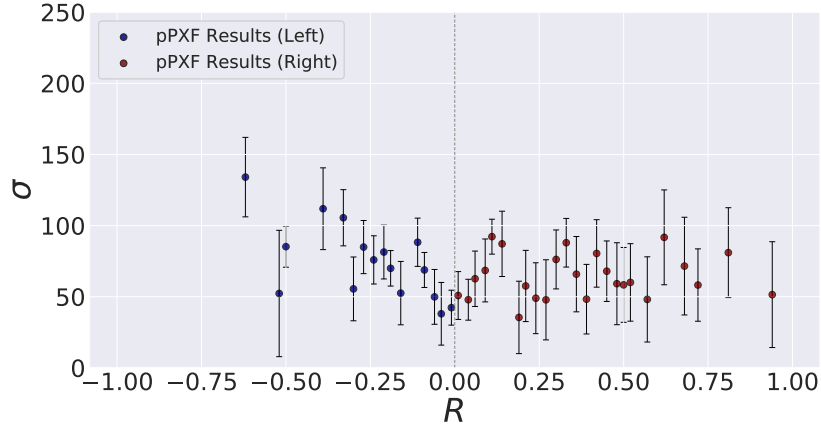


Figure F.4: Stellar velocity dispersion profile for J1153's minor axis (medium resolution).

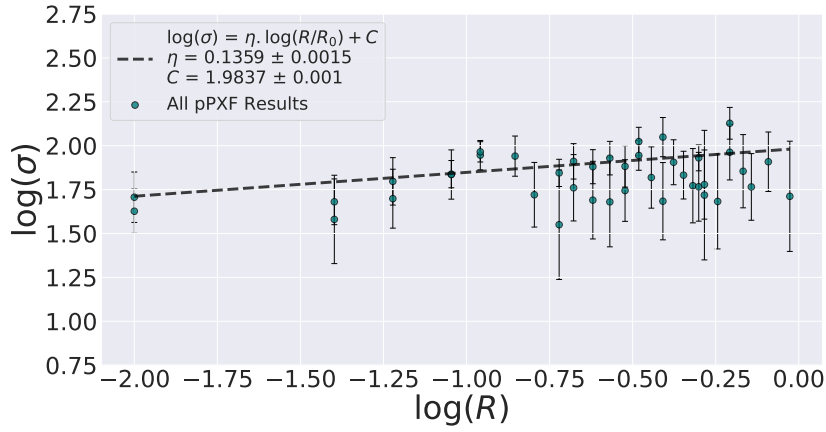


Figure F.5: Stellar velocity dispersion slope for J1153's minor axis (medium resolution). The slope is positive. The profile can be interpreted as increasing with reasonable certainty.

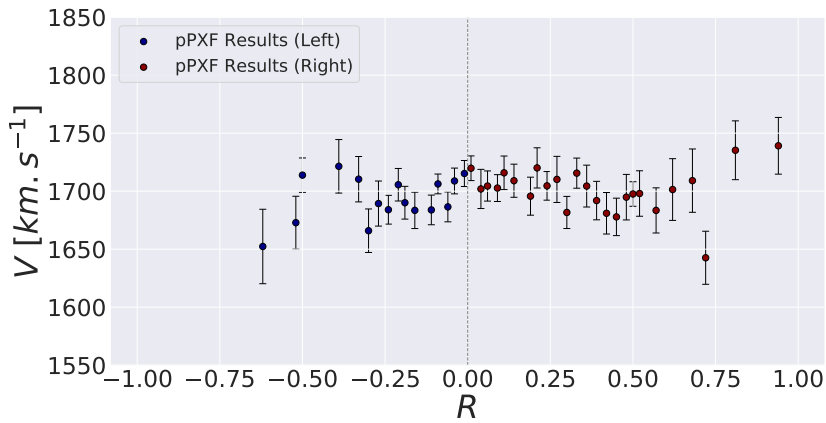


Figure F.6: Rotational velocity profile of J1153's minor axis (medium resolution). The pPXF results show that J1153's minor axis has no clear rotation.

Appendix G

Stellar Population Properties of J1153

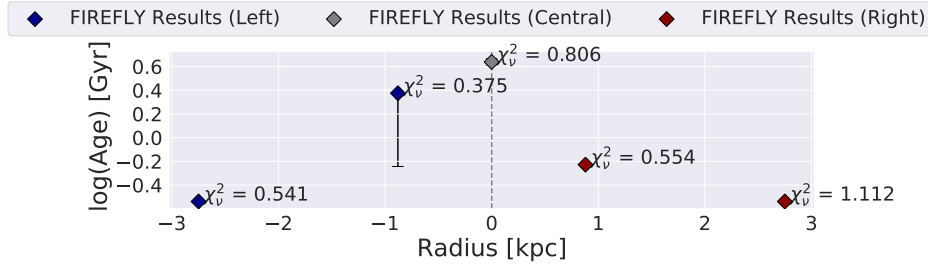


Figure G.1: Stellar population ages of J1153's major axis (medium resolution), as measured with FIREFLY using the MILES stellar library, assuming a Kroupa IMF.

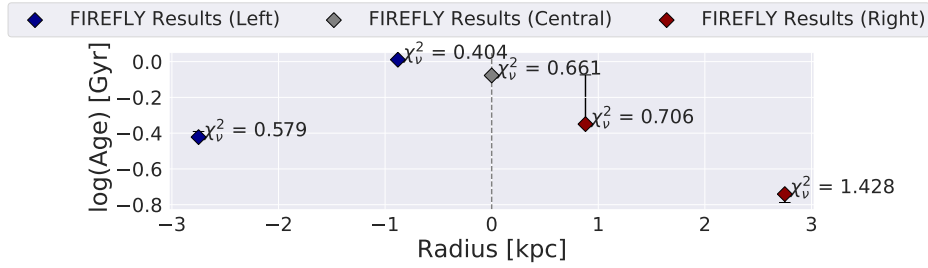


Figure G.2: Stellar population ages of J1153's major axis (medium resolution), as measured with FIREFLY using the STELIB stellar library, assuming a Kroupa IMF.

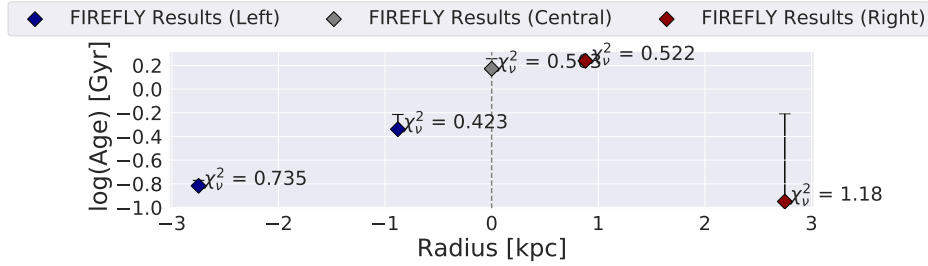


Figure G.3: Stellar population ages of J1153's major axis (medium resolution), as measured with FIREFLY using the ELODIE stellar library, assuming a Kroupa IMF.

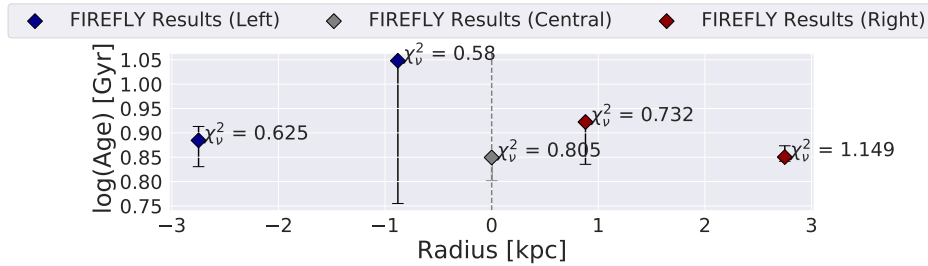


Figure G.4: Stellar population ages of J1153's major axis (medium resolution), as measured with FIREFLY using the MARCS stellar library, assuming a Kroupa IMF.

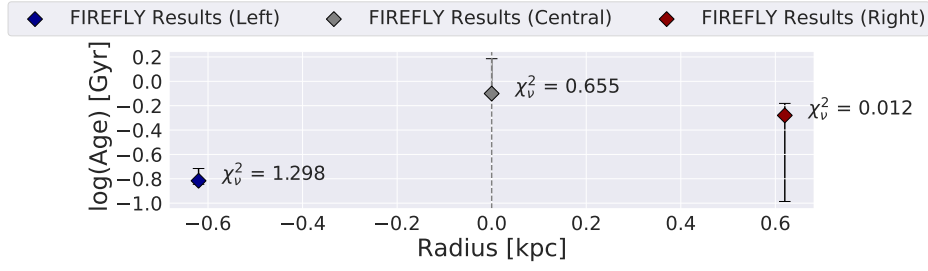


Figure G.5: Stellar population ages of J1153's minor axis (medium resolution), as measured with FIREFLY using the MILES stellar library, assuming a Kroupa IMF.

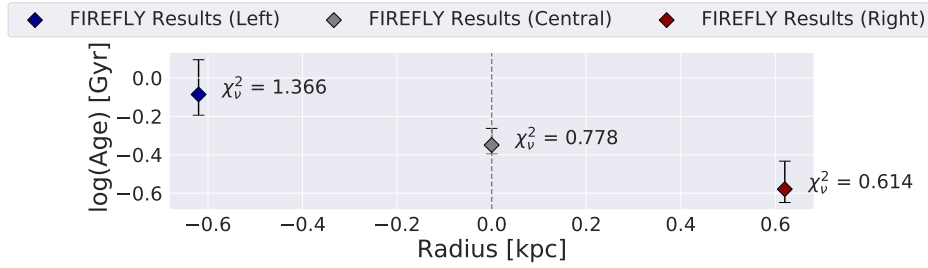


Figure G.6: Stellar population ages of J1153's minor axis (medium resolution), as measured with FIREFLY using the STELIB stellar library, assuming a Kroupa IMF.

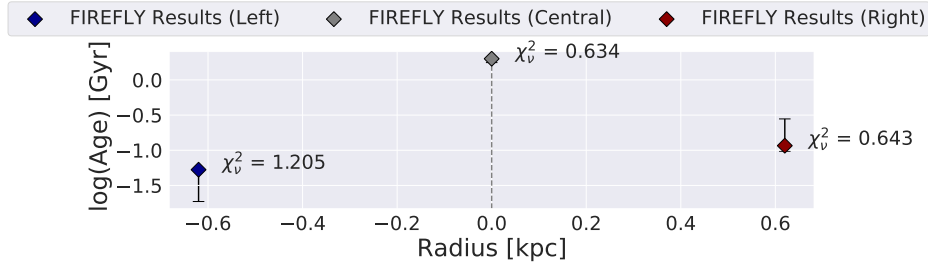


Figure G.7: Stellar population ages of J1153's minor axis (medium resolution), as measured with FIREFLY using the ELODIE stellar library, assuming a Kroupa IMF.

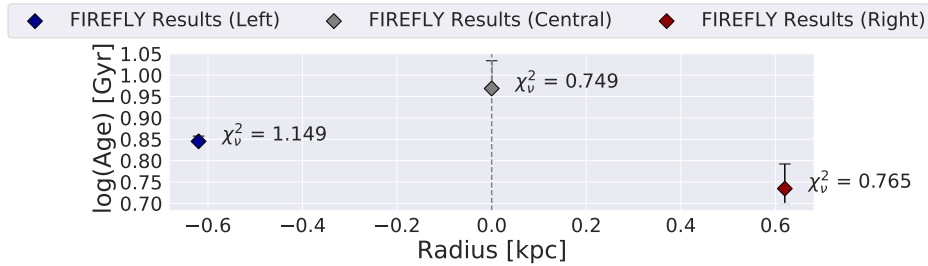


Figure G.8: Stellar population ages of J1153's minor axis (medium resolution), as measured with FIREFLY using the MARCS stellar library, assuming a Kroupa IMF.

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