THE DYNAMICAL PROPERTIES OF VIRGO CLUSTER GALAXIES

by

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Abstract

By virtue of its proximity, the Virgo Cluster is an ideal laboratory for us to test our understanding of the formation of structure in our Universe. In this spirit, we present a dynamical study of 33 gas-poor and 34 gas-rich Virgo galaxies as part of the Spectroscopic and H-band Imaging of Virgo survey. Our final spectroscopic data set was acquired at the 3.5-m telescope at the Apache Point Observatory. $H\alpha$ rotation curves for the gas-rich galaxies were modelled with a multi-parameter fit function from which various velocity measurements were inferred. Analog values were measured off of the observed rotation curves, but yielded noisier scaling relations, such as the luminosity-velocity relation (also known as the Tully-Fisher relation). Our best $i$-band Tully-Fisher relation has slope $\alpha = -7.2 \pm 0.5$ and intercept $M_i(2.3) = -21.5 \pm 1.1$ mag, matching similar previous studies. Our study takes advantage of our own, as well as literature, data; we plan to continue expanding our compilation in order to build the largest Tully-Fisher relation for a cluster to date. Following extensive testing of the IDL routine pPXF, extended velocity dispersion profiles were extracted for our gas-poor galaxies. Considering the lack of a common standard for the measurement of a fiducial galaxy velocity dispersion in the literature, we have endeavoured to rectify this situation by determining the radius at which the measured velocity dispersion, coupled with the galaxy luminosity, yields the tightest Faber-Jackson relation. We found that radius to be $1.5 \, R_e$, which exceeds the extent of most dispersion profiles in other
works. The slope of our Faber-Jackson relation is $\alpha = -4.3 \pm 0.2$, which closely matches the virial value of 4. This analysis will soon be applied to a study of the Virgo Cluster Fundamental Plane. Rotation correction of our dispersion profiles will also permit the study of galaxies’ velocity dispersion profile shapes in an attempt to refine our understanding of the overall manifold of galaxy structural parameters.
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List of Acronyms

ACS Advanced Camera for Surveys
ACSVCS ACS Virgo Cluster Survey
ALFA Arecibo L-band Feed Array
APO Apache Point Observatory
DBSP Double Spectrograph
DIS Double Imaging Spectrometer
FWHM Full-Width Half-Maximum
FJR Faber-Jackson Relation
FP Fundamental Plane
KPNO Kitt Peak National Observatory
LINER Low-Ionization Nuclear Emission-line Region
LOSVD Line-Of-Sight Velocity Dispersion
NED NASA Extragalactic Database
pPXF Penalized Pixel Fitting
PSF Point-Spread Function
RC Rotation Curve
RC Spectrograph Ritchey-Chretien Focus Spectrograph
SBF Surface Brightness Fluctuation
SDSS Sloan Digital Sky Survey
SED Spectral Energy Distribution
**SHIVir** Spectroscopic and H-band Imaging of Virgo

**SNR** Signal-to-Noise Ratio

**TFR** Tully-Fisher Relation

**VCC** Virgo Cluster Catalogue

**VD** Velocity Dispersion

**VDP** Velocity Dispersion Profile
Chapter 1

Introduction

As theoretical models of structure formation such as the Lambda Cold Dark Matter (ΛCDM) model are being built and tested against observations of the large scale structure in our Universe (Seljak et al. 2006; Komatsu et al. 2008), we appreciate that the intricacies of galaxy formation and evolution still elude our understanding. For instance, galaxy clusters provide an invaluable testing ground whereby some degree of substructure is always found (Geller & Beers 1982; Gao et al. 2012; Einasto et al. 2012). The mechanisms by which this substructure formed, however, remain somewhat mysterious. Whether galaxies came to be via secular evolution (Kormendy & Kennicutt 2004), hierarchical formation (White & Frenk 1991; Cole et al. 2000) or some combination of the two is still under investigation. Studying the internal dynamics of such cluster galaxies can give vital clues to the processes involved in their evolution. Ingrained in every velocity measurement is the history of that galaxy: tidal interactions, bar formation, mergers, etc. Better yet, spatially resolved internal dynamics can paint a picture of a galaxy’s history not only over space, but time as well. The radial distribution of velocities in a galaxy provide a fossil record of its evolution, just as its radial stellar population, metallicity and age gradients do (Roškar et al. 2008).

As a dynamically active and structurally complex system that happens to be
our nearest rich galaxy cluster, the Virgo Cluster proves to be an inestimable, yet equally challenging study subject. First observed in 1784 by Charles Messier, it was the first galaxy cluster ever discovered, though its members were not officially recognised as bona fide galaxies until the 1920s. At a distance of approximately 16.5 Mpc (Mei et al. 2007), it contains a gravitating mass of $M_{200} = (1.4 - 4.2) \times 10^{14} \, M_\odot$ (McLaughlin 1999). It is thought to contain multiple substructures named “clouds” (de Vaucouleurs 1961), that all have different internal structures, dynamics and interactions with their large-scale environment, as well as background groups (such as the W, W’ and B groups) that appear to be independent of the main cluster. The cluster’s proximity offers well-resolved views of its members, yet depth effects and significant internal motions within the cluster have thwarted accurate distance estimations and detailed 3D mapping of the cluster (Mei et al. 2007). Virgo still remains the most extensively studied galaxy cluster, not least of which because of these very characteristics. Efforts to characterise its galaxy population have been ongoing since the 1920s (Shapley & Ames 1926; Hubble & Humason 1931; Zwicky 1942; Holmberg 1958; Sandage 1972). A massive undertaking was initiated by Binggeli, Sandage and Tammann (1985) to image an area of 140 deg$^2$ around its core in blue wavelengths. Their Virgo Cluster Catalogue (VCC) has been instrumental for most subsequent studies of this cluster.

Virgo is a cluster still in the making and provides unparalleled insights to the evolutionary steps of structure in a cluster environment, as well as access to thousands of nearby resolved galaxies. Unlike the Coma Cluster and other regular galaxy clusters, its population covers a wide range of galaxy morphology. Whereas most clusters are dominated by early-type galaxies (Rood 1974), the Virgo Cluster is actually thought to contain more bright spirals than bright ellipticals (Shapley
The study of Virgo thus allows an unparalleled laboratory to study the environmental factor of galaxy evolution for disc galaxies.

The Virgo Cluster has been a subject of intense scrutiny for nearly a century now. A number of recent extensive surveys have been conducted around it: the ACS Virgo Cluster Survey (ACSVCS) in the optical (Côté et al. 2004), the Herschel Virgo Cluster Survey (HeViCS) in the infrared (Davies et al. 2010), the GALEX Ultraviolet Virgo Cluster Survey (GUViCS) in the ultraviolet (Boselli et al. 2011) and the ongoing New Generation Virgo Cluster Survey (NGVS) collaboration that endeavours to create the deepest and most complete optical map of the Virgo Cluster ever (Ferrarese et al. 2012). As we are, ourselves, interested in determining the dynamics of Virgo Cluster galaxies, we must mention past like efforts. In conjunction with their imaging survey, the ACSVCS collaboration executed a dynamical study of Virgo (NOAO Proposal ID #2003A-0195, PI P. Côté) using long-slit optical spectroscopy collected at the Kitt Peak National Observatory (KPNO) and the Keck Observatory. An international team with members based in Montréal, Paris and Marseilles led by Laurent Chemin also collected the 3D velocity fields of ionized gas for 30 Virgo Cluster galaxies (Chemin et al. 2006, hereafter C06). The Very Large Array (VLA) Imaging of Virgo in Atomic gas (VIVA) Survey has amassed imaging and 3D velocity fields in HI gas of 53 late-type Virgo Cluster galaxies (Chung et al. 2009, hereafter C09). Finally, the Arecibo Legacy Fast ALFA (ALFALFA) Survey hopes to probe a total area of 70 000 deg\(^2\) in the 21-cm radio line. It has already accumulated dynamical information in the form of line widths for a considerable fraction of Virgo galaxies (Papastergis et al. 2010).

Through our own Spectroscopic and H-band Virgo survey (hereafter SHIVir
survey), we have both compiled existing and acquired new photometric and spectroscopic observations of Virgo Cluster galaxies. So far, our SHIVir database contains data for 286 Virgo Cluster galaxies, spanning a wide range of morphology, size, brightness, and stellar populations. Moderately deep luminosity and surface brightness profiles have been extracted in the $H$-band and from the Sloan Digital Sky Survey (hereafter SDSS) by McDonald et al. 2009ab and McDonald et al. 2011. Furthermore, gradients in colour, age and metallicity have also been interpreted in terms of stellar population and radial migration effects for a large fraction of SHIVir galaxies (Roediger et al. 2011a and 2011b). This present work aims to extend our spatially resolved observations of Virgo Cluster galaxies to spectroscopically determined internal stellar dynamics. While our coverage overlaps with some previous dynamical Virgo surveys coverage, we provide novel observations for a number of galaxies. Overlapping galaxies will nevertheless be crucial in both verifying our results and comparing the dynamics of different components of the galaxies (HI and HII gas). Other 2D and 3D dynamical studies have been performed on a limited number of galaxies, whereas we hope to extend our survey to a large and representative sample of the Virgo Cluster. The ALFALFA Survey has undertaken a large number of galaxies, but their results lack crucial spatial resolution due to their sole use of line widths. Furthermore, we are the only such spectroscopic that is concentrating on both early- and late-type galaxies, as we wish to perform the largest homogeneous photometric and spectroscopic study of Virgo Cluster galaxies.

Our main goals are twofold. First, extract and study the spatially resolved velocity dispersion (VD) profiles of gas-poor galaxies in the Virgo Cluster. Prior to the advent of efficient detectors and use of large aperture telescopes, such data would require significant integration times due to the rapid (exponential) surface
brightness decay with distance. Looking deeply into these galaxies should reveal extended dynamical profiles whose shapes may, in turn, correlate with other galaxy physical parameters. An analog on a smaller scale is the Faber-Jackson (Faber & Jackson 1976, hereafter FJ76) relation (FJR) where the central VD $\sigma_0$ correlates with the total luminosity of the galaxy $M_{\text{tot}}$. One wishes to extend this kind of study to VDs measured in the outskirts of galaxies and examine largely uncharted domains in the extended dynamical profiles of galaxies. Most published velocity dispersion profiles (VDPs) have also been limited to radii within one effective radius, $R_e$. In this thesis, we wish to study the extended shapes of the VDPs.

Measurements of galaxy structural parameters also call for great uniformity in their definition in order to avoid interpretation bias. VDs are indeed fraught with confusion given their many heterogeneous definitions in the literature. VDs are often measured at a varying fraction of an effective radius, or at some pre-determined (and sometimes aperture-corrected) physical radius in kpc. A significant attempt at establishing a convention on this topic has been Jorgensen et al. (1996), and it has not been homogeneously applied nor has it been extensively physically motivated. Part of our work is to bring uniformity to this muddled scene. A possible approach to selecting an “ideal” VD is to choose the one which minimises a fundamental correlation in galaxies. The FJR is one of them; its scatter can however be further reduced through the use of a third parameter $\Sigma_e$, giving rise to a “Fundamental Plane” (FP) of gas-poor galaxies (Djorgovski & Davis 1987; Sheth & Bernardi 2012). It is indeed our goal to define the most rigorous VD measure with our SHIVir data to extract the most complete fundamental manifold of cluster galaxies to date.

Second, we wish to apply a similar analysis for gas-rich galaxies. That is, first confirm the best measure of line-of-sight velocity based on galaxy emission lines
and apply this definition to our SHIVir galaxies in order to derive detailed scaling relations. The most relevant scaling relation for spiral galaxies is the Tully-Fisher (Tully & Fisher 1977, hereafter TF77) relation (TFR) which relates the observed rotational velocity of a galaxy $V_{rot}$ with its total luminosity $M_{tot}$. Unlike the FJR, the TFR is the Fundamental Plane of gas-rich galaxies (Courteau & Rix 1999). To avoid dust effects, we concern ourselves with $i$-band photometry, as redder bands have been shown to produce tighter TFRs. The $i$-band TFR has been studied a great number of times for both field galaxies (Haynes et al. 1999a and 1999b; Mastes et al. 2006; Courteau et al. 2007; Saintonge & Spekkens 2011; Hall et al. 2012) and cluster galaxies (Giovanelli et al. 1997; Pizagno et al. 2007). Proper rotational velocity metrics have also been investigated before (Courteau 1997, hereafter C97; Giovanelli & Haynes 2002).

In addition to our own data, this thesis will involve a compilation of most existing dynamical measurements for Virgo Cluster galaxies. The literature for emission line velocities is far richer than that for absorption line velocities, simply because the former is much easier to acquire than the latter. The latter will consequently require novel observations from us. Of ultimate interest for the connection of observations with theoretical models of structure formation is to combine both types of velocity measures for all galaxies to produce a complete galaxy velocity/mass function (Dutton et al. 2011; Trujillo-Gomez et al. 2011). With our data base of accurate and homogeneous (homogenised) structural parameters of galaxies, we can not only study their scaling relations but also any difference due to environment. For instance, do scaling relations for field and cluster galaxies differ? As already briefly mentioned, there is already a large number of scaling relation studies that have been performed in the field (Haynes et al. 1999a and 1999b; Kannappan et al. 2002; Courteau et al. 2007), in galaxy clusters (Dressler
et al. 1986, 6 clusters; Piere & Tully 1988, Ursa Major and Virgo Clusters; Foqué et al. 1990, Virgo Cluster; Jorgensen et al. 1996, 10 clusters; Giovanelli et al. 1997, 24 clusters; Verheijen 2001, Ursa Major Cluster; Masters et al. 2006, 31 clusters; Toloba et al. 2011, Virgo Cluster) or a mixture of both (Bottinelli et al. 1986; McGaugh et al. 2000; Bernardi et al. 2003; Cappellari et al. 2006; Nigoche-Netro et al. 2010), yet none of these studies has attempted a comprehensive and homogeneous study of both early- and late-type galaxies from a large number of galaxies from the unique Virgo Cluster spanning all morphology types, luminosity and mass ranges save Gavazzi et al. 1999. They performed a TF and Fundamental Plane analysis of 75 late-type and 59 early-type Virgo galaxies. We note, however, that their main focus was the determination of the 3D structure of the Virgo Cluster. We consider their results as part of our SHIVir compiled data, and wish to expand upon them, probing galaxy evolution and environmental effects within the cluster as well.

The study of spatially resolved rotation curves (RCs) may also reveal signatures about the effects of the cluster environment on galaxy evolution, be it through gas stripping, galaxy mergers, counter-rotating cores or otherwise. For instance, HI and HII gas dynamics may be compared through optical and HI RCs. To reach these objectives, we require dust-free surface brightness profiles and spatially resolved 2D spectroscopy for a large number of gas-rich and gas-poor Virgo Cluster galaxies. We have already successfully observed and analysed 33 gas-poor and 34 gas-rich galaxies. Please note that these two sets overlap with 6 early-type spirals for which both rotational velocities and VDs were successfully extracted. Some of the SHIVir data were acquired by us while others were compiled from the literature. The photometric aspect of SHIVir is complete (McDonald et al. 2011a) and this thesis is entirely concerned with the necessary spectroscopy.
This thesis is organised as follows. We present the spectroscopic aspect of the SHIVir survey, the data reduction methods, and the telescope and instrument specifications used in their collection in §2. This is followed by a description of the method used in modelling our Hα RCs in §3. In §4, we go on to describe the extensive testing performed on our VD extraction method, as well as summarizing the remarks and recommendations derived from these tests. We then present our final collection of dynamical measurements of Virgo Cluster galaxies in §5. Some RCs and VDPs already measured by other authors are also compared with our own data in this chapter. We present in §6 a study of scaling relations enabled by our new extensive SHIVir data base and an overview of and comparison with other scaling relation studies. A summary and discussion about future work is offered in §7.
Chapter 2

SHIVir Data

2.1 Data Collection

The Virgo Cluster Catalog (VCC), as compiled by Binggeli et al. (1985), includes 2096 galaxies over an area of 140 deg$^2$. The VCC is believed to be complete down to a $B$-band magnitude of $M_B = -13$ and to include objects as faint as $M_B = -11$. For the purpose of SHIVir investigations, stringent selection criteria were applied to the VCC: a magnitude cutoff of $B_T \leq 16$, exclusion from the W, W$'$ and B background groups (de Vaucouleurs 1961; Ftaclas et al. 1984; Trentham & Tully 2002), identification as non-background objects by Binggeli et al. (1985), inclusion in the SDSS DR6 catalogue (for use of its multi-band photometry), position at least 6° from the central galaxy M87, a recessional velocity $V_{\text{rad}} < 3000$ km s$^{-1}$, no significant foreground star contamination, and detection in the $H$-band (McDonald et al. 2009b). These criteria reduce the VCC to a (more-or-less) magnitude-limited catalog of 286 SHIVir galaxies. Many of these galaxies have previously been observed by others, and this information was diligently compiled to enhance our work (see §6.1). While the optical and near-infrared (NIR) photometry of SHIVir is now complete, the purpose of this thesis is to collect and analyse the necessary spectroscopy to construct a complete manifold of structural
and dynamical properties of galaxies in one given cluster. In general, we endeavored to collect a spectrum (dynamical profile), whether measured in absorption or in emission, for each SHIVir galaxy with photometric data. However, given weather constraints and the finite time scales available to us in 2008, 2009, and 2012 when data were being collected, our spectroscopic catalog consists mostly of the brightest SHIVir galaxies. The fainter ones will be observed in the near future with large aperture telescopes.

Our spectroscopic observations from 2008 to 2012 were performed on 3.5-5 meter class telescopes at the Apache Point Observatory (APO) in New Mexico, the KPNO in Arizona, and the Palomar Observatory in California. The spectra in 2008/2009 were collected by Stéphane Courteau, Melanie Hall (both from Queen’s University), Mike McDonald (Massachusetts Institute of Technology) and Jon Holtzman (New Mexico State University). Nathalie Ouellette joined the team for all the observing runs at APO in 2012. Basic data reductions (see §2.2) were made by JH; everything subsequent to this is the work of NO. Some practical constraints applied to the SHIVir sample as well. To allow sky subtraction, the semi-major axis must be at least 1\' smaller than the slit length of the instrument used. For spiral galaxies, inclination must be between 20° and 70°. The lower bound is to assure that a proper amount of Doppler shift is visible to trace a visible RC. The upper bound limits the effect of thick dust lanes within the galaxy’s disc. To assure clean absorption features used in the determination of VD, early-type galaxies with significant emission were ignored. It should be noted that these criteria were not strictly enforced prior to 2012, before the author became involved in the research project. The exposure times ranged from 800s to 3600s and were scaled as a function of visual magnitude to ensure a minimum Signal-to-Noise Ratio (hereafter SNR) (see §4.1.1 for early-type galaxies). Higher levels of SNR were
required for gas-poor galaxies in order to determine VD using absorption features, as opposed to gas-rich galaxies included in our Hα RC study. The integration time scaling thusly differed between the two galaxy types.

In total, 67 early-type galaxies, 38 late-type galaxies and 2 galaxies of unidentified Hubble type were observed in the context of the spectroscopic SHIVir survey, for a total of 107 galaxies observed over 29 allocated half-nights, 23 of which were at least partially clear. After more careful examination of the 2008 and 2009 data, the 2012 SHIVir campaign galaxies were chosen to be brighter than $m_V = 13.6$ due to the size of the telescope used. Additional information on all observed galaxies may be found in Table 2.1. The parameters describing the instrumental setup of all three telescopes used can be found in Table 2.2.

2.2 Data Reduction

The preliminary data reduction, including geometrical corrections, dark and bias current subtraction, wavelength calibration, flexure correction and a first round of cosmic ray removal, was performed by JH using a suite of XVISTA routines. The result of this preliminary reduction can be seen in Figures 2.1(a) and 2.2(a). NO then proceeded with her own reductions. First, a second round of cosmic ray removal using la_cosmic (van Dokkum 2001) was performed (see Figures 2.1(b) and 2.2(b)). To better visualise the number of cosmic rays removed, maps of these comic rays were also created (see Figure 2.3). Second, the sky emission was subtracted from every observation. Leftover cosmic rays were removed by performing a 3-σ level sky-clipping. The sky background is removed by fitting and subtracting a 1st- or 2nd-order polynomial along all columns (see Figures 2.1(c) and 2.2(c)). The order function with the lowest $\chi^2$ is retained. Third, a flux calibration was applied to every observation. Every telescope run included the observation of
a few standard stars for which we also had a flux-calibrated spectrum. Using these as well as flux-calibrated star spectra available in the MILES catalogue (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011) to create a wavelength-dependent flux calibration vector, the observational flux was calibrated (see Figures 2.1(d) and 2.2(d)). At this point, the reduction method differed between RC extraction and the creation of a spectral energy distribution (SED) to extract a VD. These will be described shortly.

2.3 Variance Maps

A first noise-variance map was created by JH. The final variance maps must however account for subsequent reductions by the author such as sky subtraction and flux calibration. In accordance with the following:

\[ \sigma = \sqrt{S + 2 \cdot B}, \]  

where \( \sigma \) is the standard deviation of the noise distribution, \( S \) is the signal and \( B \) is the background that was subtracted from the signal, we add our simulated sky background created as described in the previous section to the variance maps twice. Finally, we flux calibrate the whole variance maps, just as we did with the observational spectra, in order to normalise them to the same level. The difference these two steps make can be visualised in Figure 2.4. Clearly, noise in the galaxy emission and cosmic rays dominate the noise-variance maps, whereas the subtracted sky becomes, by far, the important factor in the full variance maps.

2.4 Rotation Curve Extraction

The H\( \alpha \) emission line at 6562.8 Å was chosen to determine the RC of 34 of our gas-rich galaxies. Eventually, the [NII] lines will be included in the extraction of
our RCs to improve their $SNR$. Only the red channel was used to extract a RC, in the case of Palomar and APO observations.

The extraction of a RC requires that the flux centroids (in emission or absorption) and their errors at each pixel be properly calculated. Those centroids correspond to the velocity shifts of the RC. Variance maps are required for error assessment. The emission line region for a sample galaxy (VCC 836) is shown in Figure 2.5. The intensity-weighted centroid for each pixel row in the spectral (dispersion) direction centred around the (shifted) $H\alpha$ line can be modelled using a parabolic-binned interpolation (C97). In other words, a 2nd-order polynomial is fit at each row and the parabola’s peak is interpolated and set as the centroid wavelength at that row. The centroid for the $i^{th}$ row $\lambda_i$ is then compared to the wavelength of the emission line’s dynamical centre $\lambda_o$ using the Doppler equation:

$$\frac{V_i - V_o}{c} = \frac{\lambda_i - \lambda_o}{\lambda_o},$$

(2.2)

to find the row’s rotational velocity $V_i$ compared to the galaxy’s bulk motion $V_o$. Our spectra are all de-redshifted in order to work in the rest frame of our galaxies. The binned interpolation method also generates position uncertainties on each row’s peak, which subsequently transforms into velocity uncertainties in the raw RC. For more details on this method, see Appendix A in C97.

A preliminary estimate of the position of the true dynamical centre of the galaxy is challenging since the emission line peak may not match that centre. This is partly why galaxies with core emission activity were largely avoided. The initial step towards finding the centre of the galaxy is to find the spatial peak in pixel value along the emission line. This spatial point is set as a temporary galaxian centre. While this is a good first estimate of the galaxy’s centre, the brightest point in the emission line is not necessarily indicative of the true centre of the
galaxy’s potential well. Moreover, a non-trivial portion of our galaxies do not show a defined emission peak. To remedy this, the RCs are systematically folded at different points along their curve. To find the velocity centre, symmetry is assumed between both sides of the galaxy. The $\chi^2$ difference between each side of the galaxy is computed for each of these folding points. The folding point resulting in the smallest $\chi^2$ value is chosen as the centre of the galaxy.

Some galaxies do not have significant Hα emission across the whole width of the galaxy, and so we are left with gaps in our RCs. The intensity-weighted centroids found along these spatial rows may appear consistent, but the uncertainties associated with their velocity shifts are considerably larger than for the rows that do contain emission. In order to clean the RCs of these emission drop-outs, as well as any other problematic pixels or rows, all RC points with 1-σ uncertainties exceeding 15 km s$^{-1}$ are removed. Additionally, in order to safeguard against the effect of leftover cosmic rays, centroids with pixel values exceeding the sigma-clipped mean pixel value by 5-σ are also removed. The dynamical values extracted from these final RCs, as well as the method used in determining them, will be discussed in Chapter 3.

2.5 Stellar Dispersion Profile Extraction

Much as RCs trace the dynamics of gas-rich galaxies, VDPs measured from stellar absorption spectra provide an integrated measure of the random motion of gas-poor galaxies. This has been done several times by the likes of FJ76, Bertola et al. (1984), Bender et al. (1994) and more, yet a unifying methodology has yet to be convincingly established. Jorgensen et al. (1996) attempted to do so via the definition of both metric and normalised dispersion. The former involves a dispersion measured within a circular aperture of diameter 1.19 h$^{-1}$ kpc, independent
of galaxy size or type. The latter dispersion is measured within one quarter of an effective radius \( (R_e/4) \). Many similar definitions for VDs measured at \( R_e/4 \) (Haşegan et al. 2005), \( R_e/10 \) (Emsellem et al. 2004), or projected at \( R = 0'' \) (Halliday et al. 2001) also exist. Each method has its pros and cons. A metric aperture is easily applied since it only depends on the distance to the galaxy but it also captures different parts of a galaxy given its distance and surface density profile. A scaled aperture (e.g. relative to a fiducial radius such as \( R_e \)) alleviates distance effects but requires that the surface brightness profile be measured. Furthermore, VDPs may not be self-similar (i.e. they may not all have the same shape). Thus, in order to compare VDs amongst galaxies, the dispersion profiles must be measured out to large radii and a suitable location for the measurement of VDs must be identified to bring all VDs onto a common system. Such a system has yet to be defined and it is our goal to provide such an exercise.

In order to extract those dispersion profiles well into gas-poor galaxies, the deep extended spectra described in §2.1 provide absorption features whose profiles can be traced out to a few effective radii. We fit those absorption features using the freely available IDL routine, pPXF developed by Cappellari & Emsellem (2004). pPXF requires a logarithmically binned one-dimensional SED, rather than the two-dimensional spectra obtained at the telescope. A 2D spectral image may be turned into a 1D spectrum by summing multiple rows into one. The physical range or extent over which this summation is performed is crucial for a number of reasons: a) it may be determined via a S/N threshold criterion, b) it may encompass subtle non-similar profile variations amongst galaxies, c) it may obey rules adopted by previous observers.

Since we are mainly interested in the broadening of absorption features and wish to decrease contamination within these features by emission, only the blue
channel is used for the Palomar and APO observations. As already mentioned, pPXF requires a logarithmically binned 1D spectrum, whereas our pre-reduced data are linearly binned. In order to conform with pPXF, our 1D spectra were rebinned logarithmically using a constant velocity scale of 30 km s\(^{-1}\). More importantly, since pPXF compares our observational spectra to artificially broadened stellar spectra templates, we must choose the same velocity scale in log-rebinning both the observations and the templates. Biases involved in template choice will be discussed in §4.1.2. Ultimately, we choose a set of stellar templates from the MILES library (Sánchez-Blázquez et al. 2006). Both the template and the observed spectrum must use the same spectral resolution. We therefore convolve our spectra to match the 2.5 Å resolution (FWHM) of the MILES library over the range 3525-7500 Å. In order to apply this convolution, we must clearly determine the resolution of our own observations first. We do so in the next section.

pPXF does supply uncertainties on its VD results, but its authors (Cappellari & Emsellem 2004) do not suggest their use as they may not be accurate representations of the uncertainties. Instead, 100 Monte Carlo simulations were run for each galaxy in order to determine both the stability and the uncertainty of each VD result. Noise derived from our own variance maps was added to our observational spectrum, which was then run through pPXF. The noise of each pixel point was taken from a Gaussian distribution centred about zero with a variance corresponding to the mashed variance map value at that pixel. The standard deviation of all 100 VD results taken from all 100 spectra with noise added was taken to be the 1-σ random uncertainty of that galaxy’s VD.
2.6 Spectral Resolution

While an average spectral resolution may be specified in most spectrograph user manuals, the precise value of this parameter often fluctuates on a daily basis (often with temperature). Knowledge of the intrinsic instrumental dispersion, $\sigma_{\text{inst}}$, is of course key to extract accurate and meaningful corrected VDs, $\sigma_{\text{cor}}$. The observed, or raw, dispersion, $\sigma_{\text{raw}}$, is of course the convolution of $\sigma_{\text{inst}}$ and $\sigma_{\text{cor}}$ described in

$$\sigma_{\text{raw}}^2 = \sigma_{\text{inst}}^2 + \sigma_{\text{cor}}^2.$$  \hspace{1cm} (2.3)

Since $\sigma_{\text{cor}}$ is our goal, we must first deconvolve $\sigma_{\text{inst}}$ from $\sigma_{\text{raw}}$. The magnitude of these fluctuations appear to significantly affect the VDs computed by pPXF beyond the level of random uncertainties, and so we determine the spectral resolution as a function of wavelength for every single observing run we have performed. Many different techniques may be used to do this. One can measure the instrumental broadening of skylines. However, only one major skyline is present in the blue channel of our spectra, which is where we measure VD. Ideally, we want more than a single value to constrain the spectral resolution function. Another method would entail measuring the instrumental broadening of a standard star’s absorption features. This would require both the observation of this star using our spectrographs and a corrected spectrum of this same star in the literature which would need to have been de-broadened. Two problems arise here. First, we would need to trust that the corrected spectrum has been properly de-broadened, and this would require the original observers to have properly determined the spectral resolution function of their own instrument. Second, although relatively small, we would need to either ignore or determine the intrinsic broadening of the chosen star (rotational, pressure, etc.). With these considerations in mind, we chose to instead measure the instrumental broadening of the lamp calibration spectra observed at
each telescope before and after each run.

2.6.1 Palomar Observatory

Iron, argon, helium and neon spectral lamps were used at the Palomar Observatory. A total of 7 spectral lines were used over the wavelength range, including 5 in the blue channel. Unfortunately, in the case of the February 26 2008 observations, the broadening of 2 of these lines could not be properly determined due to heavy asymmetry in the broadening. A plot describing the spectral resolution function of the 3 observations performed at the Palomar Observatory can be seen in Figure 2.6.

2.6.2 Kitt Peak National Observatory

Argon, helium and neon spectral lamps were used at the Kitt Peak National Observatory. A total of 9 spectral lines were used over the wavelength range. A plot describing the spectral resolution function of the 4 observations performed at this observatory can be seen in Figure 2.7. The spectral resolution spikes at 4043 Å, where an Argon line is poorly resolved.

2.6.3 Apache Point Observatory

Argon, helium and neon spectral lamps were used at the Apache Point Observatory. A total of 19 spectral lines were used over the wavelength range, including 4 in the blue channel. Since this particular spectrograph was used many different times over the course of 4 years, time variation of the instrument’s spectral resolution function is both blatantly visible and tractable on a much longer timescale. This confirms that, to maximise the accuracy of resulting VD results, one must measure the spectral resolution function of their instrument on the same night that their data
were taken, unless all their spectral templates are taken with the same instrument on the same night. A plot describing the spectral resolution function of the 19 observations performed at the Apache Point Observatory can be seen in Figure 2.8.

2.7 SHIVir Photometry

The combining of photometry and spectroscopy is crucial for this work, especially for scaling relations. Two separate sets of photometric profiles were drawn up for most of our SHIVir collection of 286 galaxies: one by McDonald et al. (2009b; hereafter MM) and the other by Yucong Zhu (Harvard University, unpublished; hereafter YZ). These authors extracted $g$, $r$ and $i$-bands images from the SDSS for 285 and 742 Virgo galaxies respectively, and reduced them to produce surface brightness profiles. In the thesis, we will only use the $i$-band images and derived data products as that redder is least sensitive to selective dust extinction. A comparison of total $i$-band apparent magnitudes as extracted by MM, YZ or provided by the SDSS pipeline is shown in Figure 2.9. While a small offset can be found between MM and YZ, an even larger offset was found between either MM or ZH and the SDSS DR7 values. The latter agrees with similar comparisons reported in Hall et al. (2012). Because YZ provide magnitude errors (MM did not), we chose YZ’s photometric database for our study. The magnitude uncertainties grow exponentially as galaxies dim (see Figure 2.10).

The effective radius of a galaxy is defined as the radius enclosing half of its total light, as in:

$$
\int_0^{R_e} \Sigma(r)dr = \frac{1}{2} \int_0^{\infty} \Sigma(r)dr.
$$

(2.4)
where $\Sigma(r)$ is the radially-dependent surface brightness of the galaxy. The effective surface brightness $\Sigma_e$ is the surface brightness within that radius. Similarly, isophotal fitting over the visible portion of the galaxy yields isophotal radii at different surface brightness levels (e.g. $R_{23.5}$ measuring at an annulus of surface brightness $23.5$ mag arcsec$^{-2}$), as well as the total magnitude for the the region encompassed by $R_{23.5}$ (i.e. $M_{23.5}$). Effective and isophotal radii, as well as isophotal and total magnitudes, were determined for most of our galaxies by YZ. Disc scale lengths, $h$, or the radius at which the galaxy’s idealised exponential surface brightness profile has fallen off by a factor of $e$:

$$\Sigma(h) = \frac{1}{e} \Sigma(r = 0),$$

were only determined for galaxies with well-defined exponential discs devoid of profiles breaks (so-called Freeman type I spiral galaxies).

Inclinations were determined for each SHIVir galaxy by MM during his study of their light profiles. It should be noted, however, that neither the radii nor surface brightnesses nor magnitudes determined from these profiles have been corrected for inclination. Inclination was, however, used to correct all rotational velocities extracted by the author for this work. The issue on whether or not complete inclination-correction is required or even preferable is addressed in §6.1.1.
Table 2.1: Target List. (1) VCC designation. (2) Alternate designation. (3) Apparent magnitude. (4) Hubble type (taken from NED). (5) Heliocentric velocity (taken from NED). (6) Site of observation. (7) Month of observation, where ‘F’ signifies February, ‘A’ signifies April and ‘J’ signifies June. (8) Rotation angle of the long slit used during the observing run. (9) Whether a rotation curve (RC) or velocity dispersion (VD) was extracted, or both.

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<td>NGC4689</td>
<td>11.6 [B]</td>
<td>SAb/c</td>
<td>1616</td>
<td>APO</td>
<td>A08</td>
<td>50</td>
<td>RC</td>
</tr>
<tr>
<td>2066</td>
<td>NGC4694</td>
<td>12.1 [B]</td>
<td>SB0</td>
<td>1160</td>
<td>APO</td>
<td>F12</td>
<td>51</td>
<td>–</td>
</tr>
<tr>
<td>2087</td>
<td>NGC4733</td>
<td>12.7 [g]</td>
<td>SB0</td>
<td>928</td>
<td>KPNO</td>
<td>J08</td>
<td>59</td>
<td>–</td>
</tr>
<tr>
<td>2092</td>
<td>NGC4754</td>
<td>11.5 [B]</td>
<td>SB0</td>
<td>1347</td>
<td>APO</td>
<td>F12</td>
<td>67</td>
<td>VD</td>
</tr>
</tbody>
</table>
Table 2.2: Instrumental setup of telescopes and detectors used for data collection.

<table>
<thead>
<tr>
<th></th>
<th>Palomar (b/r)</th>
<th>KPNO</th>
<th>APO (b/r)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope</strong></td>
<td>Hale 200-inch</td>
<td>Mayall 4.0m</td>
<td>ARC 3.5m</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>CCD44-82 / CCDS</td>
<td>T2KB (2048x2048)</td>
<td>E2V CCD42-40 (2048x1024)</td>
</tr>
<tr>
<td><strong>Read Noise (e⁻)</strong></td>
<td>2.5 / 7.5</td>
<td>4.0</td>
<td>4.9 / 4.6</td>
</tr>
<tr>
<td><strong>Gain (e⁻/ADU)</strong></td>
<td>0.72 / 2.0</td>
<td>1.0</td>
<td>1.68 / 1.88</td>
</tr>
<tr>
<td><strong>Spectrograph</strong></td>
<td>DBSP</td>
<td>RC Spectrograph</td>
<td>DIS</td>
</tr>
<tr>
<td><strong>Grating (ℓ/mm)</strong></td>
<td>1200</td>
<td>632</td>
<td>1200</td>
</tr>
<tr>
<td><strong>Blaze (1st order) (Å)</strong></td>
<td>4700 / 7100</td>
<td>5500</td>
<td>Not Available</td>
</tr>
<tr>
<td><strong>Spectral Range (Å)</strong></td>
<td>3780-5430 / 6170-6880</td>
<td>3925-5430</td>
<td>4160-5420 / 6015-7200</td>
</tr>
<tr>
<td><strong>Spatial Dispersion (&quot;/pixel)</strong></td>
<td>1.0&quot; x 128&quot;</td>
<td>1.5&quot; x 5.2'</td>
<td>1.5&quot; x 6'</td>
</tr>
<tr>
<td><strong>Spectral Dispersion (Å/pixel)</strong></td>
<td>0.389 / 0.468</td>
<td>0.69</td>
<td>0.40 / 0.42</td>
</tr>
<tr>
<td><strong>Log Dispersion (km s⁻¹/bin)</strong></td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td><strong>Spectral Resolution (FWHM) (Å)</strong></td>
<td>1.8 (@ Hβ) / 1.65 (@ Hα)</td>
<td>1.8</td>
<td>2.0 (@ Hβ) / 1.5 (@ Hα)</td>
</tr>
<tr>
<td><strong>Pixel Size (µm)</strong></td>
<td>15</td>
<td>24</td>
<td>13.5</td>
</tr>
</tbody>
</table>
Figure 2.1: Steps of data reduction. Wavelength (x-axis) vs. radius (y-axis) is shown on a z-scale (as defined by IRAF). This example shows the spectrum of galaxy VCC1003 as taken in the blue regime at APO.
Figure 2.2: Steps of data reduction. Wavelength (x-axis) vs. radius (y-axis) is shown on a z-scale (as defined by IRAF). This example shows the spectrum of galaxy VCC1003 as taken in the red regime at APO.
(a) In the blue regime

(b) In the red regime

Figure 2.3: Cosmic ray maps showcasing the cosmic rays that were removed from the spectrum of galaxy VCC1003 using the IDL routine **la_cosmic**.
(a) Initial noise-variance map

(b) Full variance map after having had the simulated sky added twice, as well as having been flux-calibrated

Figure 2.4: Variance map in the red channel for galaxy VCC836 before and after the flux calibration and addition of sky subtraction noise. Wavelength (x-axis) vs. radius (y-axis) is shown on a z-scale (as defined by IRAF).
Figure 2.5: Close-up of the Hα emission line, flanked on both sides by the [N II] emission lines of galaxy VCC836. The rotation curve was extracted from within the red boxed region. Wavelength (x-axis) vs. radius (y-axis) is shown on a z-scale (as defined by IRAF).
Figure 2.6: FWHM spectral resolution function of the 2008 Palomar Observatory runs for the DBSP instrument.
Figure 2.7: FWHM spectral resolution function of the 2008 Kitt Peak National Observatory runs for the RC spectrograph.
Figure 2.8: FWHM spectral resolution function of the Apache Point Observatory runs for the DIS instrument.
Figure 2.9: Comparison of the apparent magnitudes of SHIVir galaxies as measured by YZ, MM and SDSS DR7, where $\Delta m_i = m_{i,Zhu} - m_{i,\text{other}}$. 
Figure 2.10: Uncertainties on apparent magnitude as a function of apparent magnitude $m_i$ as measured by YZ.
Chapter 3

Methodology of Rotational Velocity Measurements

3.1 Measuring Rotational Velocities

A wealth of information can be extracted from extended RCs. Velocities measured at specific fiducial radii are of interest to us due to their physical significance. The first rotational velocity of interest is the galaxy’s maximal rotation velocity, \( V_{\text{max}} \). This is an ideal concept of a constant velocity reached when the RC flattens out at large radii. However, many galaxies never extend to a regime of flat rotation; \( V_{\text{max}} \) can then be taken as the highest value of the observed RC or that of a smooth model fitted to it, as we discuss in the next section.

Another velocity metric may be taken at certain increments of a galaxy’s disc scale length, \( h \). There are typically two such values that have been extensively adopted in the literature (C97): \( V_{2.2} \) taken at \( R = 2.15h \) (which corresponds to the peak of an idealised stellar exponential disc) and \( V_{\text{opt}} \) taken at the optical radius, \( R_{\text{opt}} = 3.2h \). Since the disc scale length assumes an exponential disc model, any normalisation based on \( h \) should not be applied to Type II (truncated) spiral galaxies. For these cases, \( V_{2.2} \) or \( V_{\text{opt}} \) cannot be measured. Because many of our galaxies do not exhibit pure exponential profiles, we disregard the use of \( V_{2.2} \) and
V\textsubscript{opt} values.

We can also compute the rotational velocities at certain isophotal radii. One such traditional measurement is \( V_{\text{iso}} = V(R = R_{23}) \), where \( R_{23} \) is the radius corresponding to a surface brightness level of 23 mag arcsec\(^{-2}\). Since one of the main goals of this work is to determine the Tully-Fisher — or luminosity-rotational velocity — relation with the least scatter, we must take advantage of the fact that YZ determined a multitude of isophotal radii (at surface brightness levels equal to 23, 23.5, 24, 24.5, 25 and 25.5 mag arcsec\(^{-2}\)). The advantage of isophotal radii, rather than disc scale lengths, is the non-reliance on the shape of the galaxy’s luminosity profile. Some RCs will not extend beyond certain isophotal radii; once again, we may rely on a judiciously chosen RC model for those instead.

### 3.2 Rotation Curve Modelling

In addition to the extent of our observed RCs being a problem, the raw extracted RCs may lack hydrogen emission or be warped by spiral arms, recent tidal interactions or any number of other physical complications. This is especially true for the Virgo Cluster, as it is a dynamically young cluster in which cluster members experience a variety of environmental effects. This was explored in depth for 89 Virgo galaxies by Rubin et al. (1999) where half of the galaxies showed kinematic disturbances. Fortunately, the RC model can average over emission gaps. Warps, however, would require tilted-ring modelling (Jozsa et al. 2007) which is beyond the scope of this work (but to be revisited for HI PV diagrams by the author next year). Furthermore, as dangerous as extrapolations may be, shallow RCs may be projected at larger radii if the RC model is properly constrained. We should not discard the real possibility that the cluster environment would cause genuine gas stripping, hence the relatively shorter RCs in this cluster environment (Koopmann
Several options exist for the modelling of galaxy RCs. One of them could take advantage of a (putative) Universal Rotation Curve (URC), wherein all RCs across all morphologies and sizes would share the same general shape which is only dictated by their absolute luminosity and optical radius (Persic et al. 1996). However, the URC has been shown to fail for rapidly rising RCs (C97; Verheijen 2001; Noordermeer et al. 2007; to cite a few). As we strive to fit each RCs with full rigour, we must seek other RC fitting functions. This will be done ideally with as few free parameters as possible. C97 did attempt to fit his RCs using a very simple two-parameter arctan model:

\[
V(R) = V_0 + \frac{2}{\pi} V_c \arctan(y),
\]

where \( y = (R - R_0)/R_t \), \( V_0 \) is the velocity of the centre of rotation, \( R_0 \) is the spatial galaxian centre, \( V_c \) is the asymptotic maximum velocity and \( R_t \) is the radius at which the transition between the rising and flat parts of the RC occurs. Since our RCs have \( V_0 = 0 \) km s\(^{-1}\) and \( R_0 = 0 \), the model simplifies to:

\[
V(R) = \frac{2}{\pi} V_c \arctan \left( \frac{R}{R_t} \right).
\]

That being said, C97 found that this model did not recreate curves with sharp peaks near the turnover radius, nor did it properly constrain the \( V_c \) value in cases where \( R_t \) was small. Instead, a purely empirical multi-parameter function was found to be the best match:

\[
V(R) = V_c \frac{1}{(1 + x^\gamma)^{1/\gamma}},
\]

where \( x = 1/y = R_t/R \), \( \gamma \) controls the degree of sharpness of the curve’s turnover,
and $R_0$, $V_c$ and $R_t$ are defined as in the arctan model. Using this multi-parameter function, we model solid-body rotation — $V(R) \propto R$ — at small radii and flat rotation — $V(R) \propto V_c$ — at large radii. It was found to be the model that best described the shape of a variety of RCs. We chose to fit this model to our data with three free parameters — $V_c$, $R_t$ and $\gamma$ — using a Levenberg-Marquardt least-squares fit. We chose to include the data points from both sides of the folded RC as a single function to be fitted, with each point being weighed inversely proportional to its uncertainty. The best-fit parameters as well as their uncertainties for each fitted galaxy can be found in Table 3.1.

For all model RCs, we measure the maximum circular velocity, $V_{\text{max}}$, as the maximum of $V(R)$. For those galaxies which do not extend beyond a certain isophotal radius, we may rely (upon examination) on a model extrapolation to compute “isophotal” circular velocities. We may still encounter cases where the RC does not flatten or it has not been successfully fitted by our model. In those few cases, we use the rotational velocity at the maximum radius where signal was detected.
Table 3.1: Parameters of the best-fit multi-parameter functions for the observed RCs. Only galaxies which were successfully fitted with a constrained function are included here.

<table>
<thead>
<tr>
<th>VCC</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$R_t$ (\arcsec)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>483 (Feb2009)</td>
<td>139 ±4</td>
<td>21.0 ±0.5</td>
<td>0.95 ±0.04</td>
</tr>
<tr>
<td>483 (Apr2009)</td>
<td>112 ±1</td>
<td>33.7 ±0.3</td>
<td>1.48 ±0.04</td>
</tr>
<tr>
<td>559</td>
<td>124 ±2</td>
<td>30.8 ±0.3</td>
<td>1.62 ±0.04</td>
</tr>
<tr>
<td>570</td>
<td>131 ±1</td>
<td>22.8 ±0.2</td>
<td>3.8 ±0.2</td>
</tr>
<tr>
<td>664</td>
<td>51 ±6</td>
<td>33 ±3</td>
<td>17 ±12</td>
</tr>
<tr>
<td>692</td>
<td>41 ±3</td>
<td>1.6 ±0.3</td>
<td>0.68 ±0.8</td>
</tr>
<tr>
<td>768</td>
<td>81 ±2</td>
<td>13.9 ±0.3</td>
<td>3.7 ±0.3</td>
</tr>
<tr>
<td>801</td>
<td>158 ±58</td>
<td>36 ±11</td>
<td>1.7 ±0.4</td>
</tr>
<tr>
<td>836 (Feb2009)</td>
<td>175.6 ±0.9</td>
<td>66.4 ±0.4</td>
<td>6.1 ±0.4</td>
</tr>
<tr>
<td>836 (Apr2009)</td>
<td>181 ±1</td>
<td>93.6 ±0.6</td>
<td>28 ±10</td>
</tr>
<tr>
<td>865</td>
<td>69.0 ±0.4</td>
<td>19.7 ±0.2</td>
<td>4.4 ±0.3</td>
</tr>
<tr>
<td>874</td>
<td>124 ±19</td>
<td>10.1 ±0.7</td>
<td>0.8 ±0.1</td>
</tr>
<tr>
<td>958</td>
<td>178.6 ±0.6</td>
<td>26.7 ±0.1</td>
<td>3.36 ±0.09</td>
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<td>1126</td>
<td>162 ±20</td>
<td>7.0 ±0.3</td>
<td>0.62 ±0.07</td>
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<tr>
<td>1410</td>
<td>111 ±12</td>
<td>15 ±1</td>
<td>1.1 ±0.2</td>
</tr>
<tr>
<td>1486</td>
<td>112 ±31</td>
<td>23 ±6</td>
<td>24 ±9</td>
</tr>
<tr>
<td>1508</td>
<td>57.8 ±0.8</td>
<td>23.2 ±0.4</td>
<td>20 ±6</td>
</tr>
<tr>
<td>1516</td>
<td>126 ±5</td>
<td>6.6 ±0.2</td>
<td>0.67 ±0.03</td>
</tr>
<tr>
<td>1532</td>
<td>45 ±2</td>
<td>18.0 ±0.7</td>
<td>22 ±8</td>
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<tr>
<td>1811</td>
<td>76 ±10</td>
<td>13 ±1</td>
<td>0.9 ±0.2</td>
</tr>
<tr>
<td>1859</td>
<td>85 ±9</td>
<td>17 ±1</td>
<td>1.2 ±0.1</td>
</tr>
<tr>
<td>1929</td>
<td>68 ±1</td>
<td>25.1 ±0.4</td>
<td>14 ±6</td>
</tr>
<tr>
<td>1943</td>
<td>138.1 ±0.9</td>
<td>8.62 ±0.09</td>
<td>16 ±11</td>
</tr>
<tr>
<td>1972</td>
<td>89 ±8</td>
<td>4.1 ±0.5</td>
<td>0.56 ±0.06</td>
</tr>
<tr>
<td>2058</td>
<td>130 ±10</td>
<td>0.8 ±0.1</td>
<td>0.35 ±0.03</td>
</tr>
</tbody>
</table>
Chapter 4

Methodology of Measuring Velocity Dispersions

A two-dimensional spectrum can be collapsed in the spatial direction, over a pre-defined spatial range (or aperture), to create a one-dimensional SED for a gas-poor galaxy. The VD of the galaxy can then be measured from this SED using \textit{pPXF} through a series of careful operations and choices. These choices include $S/N$ requirements, stellar template data base, and aperture radius. We vary the values of each of these parameters in \textit{pPXF} in order to assess their impact on VDs. We also simulate fibre aperture with our long-slit spectra to compare with SDSS VD measurements, and remind the reader about redshift corrections to our spectra.

4.1 \textit{pPXF} Testing

4.1.1 Signal-to-Noise Requirements

In order to study the signal-to-noise dependence of our measured VDs, we can create artificial galaxies using spectra of stars typically found in early-type galaxies and artificially broaden the galaxy’s summed spectrum to a predetermined value to be recovered by \textit{pPXF}. We will use our mock spectra to determine the level of noise beyond which a VD cannot be reliably recovered. Our analysis is twofold: first, compare the VD as computed by \textit{pPXF} to that of our artificially broadened
galaxy; second, visually inspect the quality of the pPXF fit to the SED of our mock galaxy. To simulate early-type galaxies we took spectra for 3 K-type and 1 G-type stars from the MILES library. These four spectra were added together and subsequently convolved with a Gaussian of a predetermined width. Four different widths were tested: 100, 150, 200 and 250 km s\(^{-1}\).

Since pPXF is insensitive to the absolute flux level of the input SED, the number of stars (i.e. relative intensity of our spectra) is inconsequential. In fact, 1D spectra are often divided by their own median to avoid possible numerical issues and for proper normalisation. We can then degrade our composite mock spectra with varying levels of signal-to-noise, and feed them to pPXF; the recovered VD should be close to the width of the convolution Gaussian. Noise is added to the composite spectrum according to the standard definition of SNR:

\[
SNR = \frac{S}{N} = \frac{\text{Signal}}{\sigma_{\text{noise}}},
\]

\[
\sigma_{\text{noise}} = \frac{\text{Signal}}{SNR}.
\]

The noise to be added to the spectrum at each wavelength bin is chosen randomly from a Gaussian distribution centred about 0 with a \(\sigma\) value of the aforementioned \(\sigma_{\text{noise}}\).

The relative offsets between the pPXF results and the expected VDs as a function of \(SNR\) are plotted in Figure 4.1. All four tested widths are shown. Results are fairly consistent in all four cases. Error bars are nearly negligible at \(SNR\) levels of 40 per pixel and up. A slightly less stringent cutoff would be at an \(SNR\) level of 20 per pixel, where errors are around 15%. Below this point, the accuracy of the results begins to diverge and the uncertainties blow up. The total scatter in \(\Delta\sigma/\sigma\) (see Figure 4.2) is very close to 0 above \(SNR = 40/\text{pixel}\), and remains fairly low at
levels of 15-20 per pixel. In this thesis, we have used a cutoff of $SNR = 20$/pixel to be sufficient to ensure the reliability of our results. In hindsight, a value of $SNR = 40$/pixel would likely be safer.

To further solidify our decision, we visually inspect the goodness of the pPXF fit for varying levels of signal-to-noise (see Figure 4.3 for the 200 km s$^{-1}$ case, where the H$_\beta$ feature is plotted). The choice of $SNR$ of 20/pixel results in a reliable fit. Note that even the noiseless case does not result in a perfect fit between the simulated galaxy spectrum and the template fit. This is because the template is made of a linear combination of real stellar spectra. As we are basically matching observation with observation, it may be difficult, or perhaps even impossible, to get a perfect fit. This depends heavily on the template choice, which we will touch upon next. To conclude, it is imperative to consider the quality of one’s data when determining VD using pPXF. Spectra that are too noisy will result in poor spectral fitting and inaccurate VD results. The choice of telescope aperture, spectrograph, slit width, and exposure time will clearly all impact the final $S/N$ per pixel.

### 4.1.2 Stellar Template Choice

The choice of stellar templates used in pPXF can not only greatly affect the accuracy of results, but also the efficiency of the program. pPXF guidelines call for the use of approximately 100 to 200 stellar templates, anticipating about 10% of them to be retained in the galaxy spectrum fits. However, one cannot expect reliable results without consideration of the type of template used. As a test, we chose 25 stellar spectra from the MILES catalog, only recording their spectral types and ensuring that they were not extremely uncommon or unimportant in early-type galaxies (i.e. no variable stars, O-type stars, etc.). Let us call it our “random” set. We also have access to 50 stellar spectra hand-picked from the MILES catalog.
by our colleagues Lorenzo Morelli and Enrico Maria Corsini from the Università dei Studi di Padova. Short of MILES ID or spectral type information for any of the “Padova” stars, a least-squares fitting code was written to find the best match for each of these spectra in the whole MILES catalog containing over 900 stars. Unsurprisingly, they were found to be an even mixture of F and K-type stars.

We ran the same SHIVir spectra through pPXF using both the “random” and “Padova” stellar templates and compared the results. Often lacking a trustworthy literature source for a VD to compare our quantitative results to, we chose instead to visually inspect the spectral fit produced by pPXF. In nearly all cases, we found the Padova library to give far better fits to our SHIVir galaxy spectra. See Figure 4.4 for a comparison of the H\(\beta\) feature of galaxy VCC778 as fitted using the Padova and random libraries for a representative example. While both template sets follow the general shape of the observed H\(\beta\) feature, the Padova library is clearly more successfully in doing so. This is confirmed by its \(\chi^2\) values being smaller than those with the random library. In cases where we did have published VD to compare with, the Padova library again gave results that were more consistent with those found in the literature.

We also tried improving upon our results obtained with the Padova library by using the whole MILES catalog as a template library when using pPXF and found the results to be effectively the same. The use of the whole MILES library made the analysis of each galaxy nearly 20 times longer. Due to our need for Monte Carlo simulations for all differently sized apertures on our spectra to determine uncertainties on our VDs, such long computations would be prohibitive. Key for the efficiency of this program is to select a small library of carefully picked stellar templates. We therefore adopt the Padova set in subsequent reductions.
4.1.3 Aperture Bias

A major motivation for the extensive testing of input parameters in pPXF is to determine the radial variations of the VDP. With $SNR > 20$/pixel, pPXF generally matches the observed SED at all radii. For example, see the H\textbeta feature for VCC778 in Figure 4.5 as fitted using three different apertures normalised by $R_e$. While the feature itself does visibly change depending on the aperture, the goodness-of-fit is essentially the same at all radii. Thus, while the resulting VD will surely differ depending on the aperture size, it can be assumed that pPXF is accurately extracting the result independent of the aperture size, so long at the $SNR$ level is higher than 20 per pixel.

An additional VD value was determined from our data: $\sigma_o$. There are a variety of definitions in the literature for this value. Some take it to be the VD measured within an aperture of radius $R_e/8$ (Ferrarese & Merritt 2000). Others take it to be an extrapolated zero-point of the profile (Koopmans & Treu 2002). We chose the second definition. For a more involved study, some may decide to model the whole profile using a model, such as the Klypin model (Klypin et al. 2002), but we instead opted to simply draw a line through the innermost 4 points of the velocity profile intersection with the $R = 0''$ point.

We will revisit the determination of the VD, or sigma, profiles in §5.3.

4.1.4 Comparisons with the SDSS

While many spectrographs operate in long-slit mode, including the ones used in our SHIVir survey, fibres may also feed the spectrograph. Such a fibre mode was adopted for the SDSS database with fibres 1.5$''$ in radius. In order to compare our long-slit spectra with those from the SDSS, we can mash spatially over the SDSS aperture. This can be done with the 7 SHIVir galaxies that overlap with
the SDSS DR7 catalog (Adelman-McCarthy et al. 2009). The SDSS spectral resolution function was provided to us by Patricia Sánchez-Blázquez (2011, private communication). In the APO blue channel range of approximately 4160 to 5420 Å, where our VDs are measured, the SDSS FWHM is approximately 2.7 Å. Thus, the MILES templates used by \texttt{pPXF} must be degraded to that value to match the SDSS spectra.

One must now recall that the SDSS VDs were not extracted through \texttt{pPXF}. Their choice of algorithm could potentially induce a bias. Figure 4.6 shows the VDs as measured by us from the SDSS spectrum and the value provided by SDSS collaboration for the 7 overlapping galaxies in the SDSS DR7 catalog. The comparison is generally quite good. The only outlier is VCC1126, likely due to its fainter magnitude. It has a $SNR$ of 16/pixel at 1.5$''$, which is well below our cut-off of 20/pixel. If we remove that galaxy, the scatter is as small as 4 km s$^{-1}$. \texttt{pPXF} thus returns values that agrees with the SDSS dispersion algorithm. However, applying \texttt{pPXF} to our SHIVir spectra instead yields a significantly noisier comparison with the SDSS measured dispersion (see Figure 4.7). There is no obvious bias between the two sets. Rather, we only see an increase in the scatter about the 1-to-1 line. While we cannot identify a systematic bias between our values and those determined from the SDSS spectra — the small overlap of the two catalogs is a considerable obstacle for this — we must remain skeptical of VDs measured at such small radii. In brief, while the SDSS database is invaluable to the world of astronomy, the automation of the data’s analysis requires some caution on the user’s part. In the case of VDs, we believe a long-slit spectrograph to be a preferable method.
4.1.5 Redshift Effects

The computation of rest frame features like a VD requires that the input spectra be first “de-redshifted”. Given the redshift of the galaxy, \( z = \frac{v_r}{c} \), this is simply done by dividing the spectrum wavelength range by \( 1 + z \), as in:

\[
\frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = 1 + z.
\] (4.3)

Accurate redshifts may not be available for all galaxies. The heliocentric redshifts found in the NED library (as cited in Table 2.1) may differ by 5 to 10 % from those determined by pPXF. The latter allows for a small log-space shift of the templates for proper alignment with the galaxies spectra. We have verified that this effect plays no role in our derived VDs.

4.2 Velocity Dispersion Extraction

Through the experiments described above, we have determined that \( SNR > 20/\text{pixel} \) spectra are required and that the “Padova” stellar templates yield the most reliable VDs. Our spectra were also all de-redshifted. Note finally that the few pixels over the central portion of the spectrum affected by atmospheric seeing were omitted in our SED mash. Ultimately, only galaxies observed at APO passed our \( SNR > 20/\text{pixel} \) requirement and resulted in fittable SEDs. A few galaxies from Palomar and KPNO met the \( SNR \) threshold, but produced odd, jagged spectra and were ultimately re-observed at APO at a later date.

While we did determine the spectral resolution function for the APO spectrograph, only 4 spectral lines could be used to constrain it in the blue channel, the first of which being near 4500 Å, which is over 300 Å beyond the start of the wavelength range. Much of the resolution function thus remains unconstrained.
Even between points that we could measure, we had to assume linearity which may be wrong. Considering these circumstances, it was decided to instead apply pPXF twice to each spectrum, using two different levels of degradation prescribed by maximum excursions of our spectral resolution function: the maximum and minimum values of the blue channel APO spectral resolution function of each galaxy’s observation date. This gives us a range of VD at every aperture point. We felt this to be necessary, as a change of a few tenths of an Å in spectral resolution seemed to result in up to 20% effects on VD. This is illustrated in our VDPs in Appendix B. Additionally, this value range due to the uncertainty in the spectral resolution function is written down separately from the usual 1-σ random uncertainty found in the results table of §5.3.
Figure 4.1: Relative difference in velocity dispersion results as compared to the simulated galaxies’ actual broadening $\Delta \sigma / \sigma$ as a function of $SNR$. The $1 - \sigma$ uncertainties are plotted for each point. Four different levels of broadening (100, 150, 200 and 250 km s$^{-1}$) were tested.
Figure 4.2: Total scatter in $\Delta \sigma / \sigma$ (see in Figure 4.1) as a function of $SNR$ across all four broadening levels tested.
Figure 4.3: Comparison of the pPXF fits of the H$\beta$ feature on simulated galaxy spectra of varying S/NRs.
Figure 4.4: Comparison of the pPXF fits of the H$\beta$ feature on galaxy VCC778 as fitted using the template library provided by our Padova collaborators and a randomly put together library taken from MILES.
Figure 4.5: Comparison of the pPXF fits of the H\(\beta\) feature of galaxy VCC778 measured over apertures of different radii.
Figure 4.6: Velocity dispersions of the 7 overlapping galaxies extracted from the SDSS spectra as analysed through the SDSS pipeline and by us. The outlier, VCC1126, may have a poor $SNR$ within the SDSS aperture.
Figure 4.7: Comparison of the velocity dispersions extracted from the SDSS spectra to our own SHIVir spectra.
Chapter 5

Results

5.1 Rotation Curves

The RCs shown in Appendix A were successfully extracted for 34 gas-rich galaxies. RCs may be plotted against projected radius, in arcseconds, or scaled by a fiducial radius such as the effective radius, $R_e$. Exponential disc scale lengths have often been used for such radial normalisations, but as the latter are ill-defined for Type II disc galaxies, we opt for $R_e$.

Even after removing all velocity points with uncertainties exceeding 15 km s$^{-1}$, we do not find very many gaps in our RCs. However, we do find that many RCs do not extend as deeply as their corresponding light profiles. As previously stated, this may very well be due to gas stripping prevalent in the Virgo Cluster (Koopmann et al. 2006; C09). C97 determined the optical RCs of 304 field galaxies and often reached the flat rotation regime at up to 6 disc scale lengths, or roughly 3.6 $R_e$. In §5.4.1, we will further compare our RCs with other published Virgo Cluster RCs. We also wish to determine rotational velocities at specific isophotal radii directly from the observational data and to compare them with those extrapolated from the multi-parameter function fit. This could only be done out to a maximal isophotal radius $R_{23.5}$ for eleven galaxies. A total of 16 galaxies extend out to $R_{23}$. All other
RCs could not be included in this part of the study. We also successfully computed a $V_{\text{max}}$ for all 36 observations, choosing one of the methods aforementioned in §3.1. These results can be found in Table 5.1.

Given the limited extent of some of our RCs, we extrapolated a multitude of rotational velocities using our multi-parameter function fit. Eleven galaxies could not be fit by such a function with constrained parameters. Furthermore, the isophotal radii of two galaxies (VCC483, VC836) were not computed in our catalog and so it was impossible to determine rotational velocities at specific isophotal radii for these, both from observations and the fit. All rotational velocities extrapolated from our fits may be found in Table 5.2. All rotational velocities cited in Tables 5.1 and 5.2 have been corrected for inclination. A statistical study of scaling relations based on these results is presented in §6.1.

Appendix A presents our individual RCs and the multi-parameter function fits (when determined). Many of our galaxies are also found in the studies of Rubin et al. (1980, 1997, hereafter R97), C06, and VIVA (see §5.4.1); when available, these are also overplotted in Appendix A. R97 made use of 2D optical spectroscopy, measuring H$\alpha$ RCs, whereas C06 and VIVA obtained 3D spectra, and extracted fully spatially resolved velocity fields from them. C06 and C09 measured optical (H$\alpha$ emission) and radio (21-cm line) RCs respectively. A brief analysis of every individual galaxy for which an RC was successfully extracted can be found in §5.5.1.

5.2 SNR

To assess the reliability of our VDPs, we must compute the $SNR$ as a function of radius for our early-type galaxies. This is illustrated in Figure 5.2. The cutoff level of 20/pixel, which only two of our galaxies (fainter than 13 mag) do not meet, is
indicated as a dashed line.

### 5.3 Velocity Dispersion Profiles

VDPs were successfully determined for 33 galaxies over 36 observations. As previously stated, points were only kept if their $SNR$ was greater than $20$/pixel to assure reliable results. In order to facilitate our statistical study of FJRs found in §6.2, we interpolated a multitude of VDs at different fractions of $R_e$. These results can be found in Tables 5.4 and 5.5. Both the random uncertainty and the uncertainty related to the spectral resolution of our instrument are cited, and are done so separately for clarity.

For an overview of the shape of our VDPs, see Figure 5.3. The great majority of these profiles appear to follow the same general shape: a steep rise within $0.5$-$1.5\ R_e$ and a flattening out of the curve. However, a few galaxies appear to have sigma drops at larger radii. We expect all VDPs to drop after a certain radius. We have, however, not corrected for rotation in those profiles; this will be done shortly. That operation will also yield the RCs of our 33 gas-poor galaxies. We will look to the works of Mehlert et al. (2000), MacArthur et al. (2009) and others to compare the shapes of our profiles, looking for a dependence of the shape on some third parameter such as Hubble type or luminosity profile shape (cored / coreless, as described by Kormendy & Bender 1996).

We plot in Appendix B the VDPs in units of $R_e$ to get a better sense of the physical shape of the profiles. A brief analysis of notable VDPs is featured in §5.5.2.
5.4 Comparison with Other Work

5.4.1 Rotational Velocities

RCs for Virgo Cluster galaxies have been studied by many, and we are able to compare ours with theirs. This includes 13 SHIVir galaxies in common with the Hα RC collection of R97, 7 galaxies in common with the Hα RCs of C06, and 10 galaxies in common with the HI sample of VIVA. These can all be seen in Appendix A. Overall, our RCs match those found in the literature well. See §5.5.1 for more details.

Any concerns about the shallowness of our RCs can be alleviated as the extent of our RCs seems comparable to that of the other two optical studies by R97 and C06. In a few rare cases, we even seem to extend beyond some VIVA HI curves (e.g. VCC483). In those cases, we suspect that the HI disc has been more heavily stripped by the cluster environment.

Besides resolved RCs, a multitude of integrated velocity measurements are available for use. We choose to compare our $V_{\text{max}}$ values with those of R97 (as measured by the author from provided RC data), Fouqué et al.’s (1990, hereafter F90) $W_{50}/2$ and the ALFALFA survey’s $W_{50}/2$ values (Haynes et al. 2011, Papastergis et al. 2011), which are closely equivalent to $V_{\text{max}}$. Recall that the R97 data were taken in the optical using 2D spectra, while the ALFALFA and F90 data were taken at the 21-cm radio line using 1D spectra. 22 SHIVir galaxies overlap with ALFALFA. As previously stated, 13 galaxies overlap with the R97 sample. In Figure 5.4, where we plot the residuals of our comparison, it is clear that our results agree best with those of ALFALFA and F90. There is, however, one outlier in ALFALFA: VCC958. This issue is discussed in §5.5.1, along with all other anomalies in our comparisons. We compute the correlation coefficient, scatter and zero-point offset for the comparisons with each data subset as well as all sources
in Table 5.3. The offset and scatter of the Rubin dataset are quite large, but this is mostly due to three outlying galaxies. Our data agree well with the other two datasets.

### 5.4.2 Velocity Dispersions

Numerous sources of stellar VD of Virgo Cluster galaxies exist (Tonry 1981; de Vaucouleurs & Olson 1982; Dressler 1984; Davies et al. 1987; Djorgovski et al. 1987; Bender et al. 1994; McElroy 1995; Halliday et al. 2001; Gavazzi et al. 2003; Paturel et al. 2003; SDSS DR7; Oh et al. 2011) many of which overlap our own sample. Very few have explored the radial VDPs (or LOS velocity distributions) of Virgo Cluster galaxies (Bender et al. 1994; Halliday et al. 2001; Hinz et al. 2003; van Zee et al. 2004) and we find very few overlapping galaxies with them. Once we perform rotation correction on our own dispersion profiles, we will compare their shapes with the few available Virgo profiles found in the literature. While VDPs have not been very actively explored before, we have, nevertheless, created a residual plot of the comparison between the SHIVir catalog and all other VD sources with overlapping galaxies (see Figure 5.5). Forcing a one-to-one relation, we found an offset of \(2.57 \pm 0.09\) km s\(^{-1}\) between our values and those of others. Other sources quote the central stellar VD \(\sigma_o\) as their result yet most do not specify the aperture over which the VD was measured. This lead us to use our own \(\sigma_o\) in the comparisons, even though we ourselves found this measurement to be the least reliable and give the FJR with the most scatter. In addition, we suspect the amount of nebular emission in a galaxy might affect the \(p\text{PXF}\) fitting algorithm. While it appears, upon visual inspection, that \(p\text{PXF}\) is not affected by such emission, we decided to investigate strong emission as a possible bias factor in the measurements of our VDs. Figure 5.6 shows such a comparison for galaxies
identified as significant nebular emitters and for more quiescent galaxies.

Visually, it does appear that the scatter for galaxies with emission is larger than for those without. The best-fit intercepts, as well as the correlation coefficient and standard deviation for each sample can be found in Table 5.6. Proper statistics confirm that pPXF fits galaxies with nebular emission more poorly than the quiescent ones. Our next round of reductions will include a more stringent masking of regions with nebular emission before feeding our SEDs into pPXF.

We compare our results with those of ACSVCS separately, since we know the exact aperture ($R_e/4$) over which the ACSVCS VDs were measured. We also have their adopted $R_e$, and we can therefore use the same aperture as them to compare with our results. The great majority of their spectroscopic data were taken at KPNO using the GoldCam spectrometer attached to the 2.1 m telescope. The wavelength range of their observation is quite similar to ours and they used the same algorithm, pPXF, so we expect results to match up quite well. The residual plot can be seen in Figure 5.7 and the zero-point intercept can be found in the fourth row of Table 5.6. We find an encouragingly tight correlation between our results and those of ACSVCS. We do however observe a systematic offset of $10.6 \pm 0.1 \, \text{km s}^{-1}$ between the two sets, despite the many similarities between our respective data reduction methods. We investigated if these differences were due to different position angles. Figure 5.8 shows the VD discrepancies versus positional angle; no convincing correlation can be found. In fact, the galaxy with the most divergent VDs is also the one with a nearly identical PA. The systematic offset between our and ACSVCS’s dispersions is mostly likely due to our not yet having corrected our VDPs for rotation.
5.5 Individual Galaxy Description

5.5.1 Rotation Curves

We will briefly analyse the RCs and resulting rotational velocities of all 34 of our gas-rich galaxies (6 of which are early-type spirals that also have a VDP associated to them).

\textit{VCC483}: The H$\alpha$ curve extends farther out than the HI curve, which may indicate considerable HI stripping in this galaxy. Additionally, the HI curve is asymmetrical and shows an unusual scooped shaped as well as dipping down to faster receding velocities than the H$\alpha$ gas. VCC483 is only 11 kpc away from fellow Virgo member VCC497 (for which we have no spectrum). It may be that the galaxy pair is interacting and causing an asymmetry (C09). We see a small dip in our velocity curve at approximately 50$''$. This dip is shown symmetrically on both sides of the galaxy in the February 2009 observation, whereas it is only visible on the approaching side, but is much more pronounced in the April 2009 observation. This galaxy is thought to contain a weak ring, which may be distorting the curve. According to our RC, it would seem that if such a ring were indeed present, it would appear to be rotating more slowly than the disc. Ignoring this warp, our curve matches that of C06 well. Our resulting $V_{\text{max}}^c$ matches that of F90 quite well. Small differences between the RCs extracted on our two separate observations may be due to small differences in the rotation angle of the slit. Emitting gas pockets moving at different velocities may be observed or ignored depending on this angle. No ALFALFA or R97 measurements were available.

\textit{VCC559}: This galaxy is a fairly inclined system (78$^\circ$). While our result for $V_{\text{max}}^c = 107 \pm 13$ km s$^{-1}$ matches that of R97, 106 $\pm$ 9 km s$^{-1}$, very closely, there is a large discrepancy in the shape of the RC. The rapid rise of Rubin’s curve is a signature of a barred galaxy, yet no such bar has been identified in the galaxy.
Our $V_{max}^c$ also matches the ALFALFA measurement of $W_{50}^c/2 = 112 \text{ km s}^{-1}$, as well as another HI survey’s value of $W_{50}^c/2 = 107 \pm 14 \text{ km s}^{-1}$ (Helou et al. 1984) and F90’s HI line width of 106 km s$^{-1}$. That being said, the difference between our H$\alpha$ curve and that of Rubin remains puzzling. A third spatially resolved RC would be required for comparison.

570: This early-type spiral has been classified as edge-on. Our measure for $V_{max}^c = 135 \pm 1 \text{ km s}^{-1}$ matches the HI result, $W_{50}^c/2 = 135 \pm 12 \text{ km s}^{-1}$, of Helou et al. (1984) perfectly. We have also extracted a VDP for this galaxy.

VCC664: This galaxy, classified as an IBm, is quite messy. Despite being of an intermediate magnitude of $m_B = 13.5$, we find its rotational velocity to be quite low. This would be expected in such a disorganised system. This characteristic is also seen in the large uncertainties of the RC points, especially on the approaching branch of the galaxy. Nevertheless, we find our value of $V_{max}^c = 63 \pm 32 \text{ km s}^{-1}$ to match ALFALFA’s $W_{50}^c/2 = 59 \text{ km s}^{-1}$ very well.

VCC692: This galaxy is a barred system that also contains a weak ring. We see the presence of the bar in the steep rise and very small turnover radius in the RC, as well as a dip in rotation at approximately 0.5 $R_e$ on both sides of the RC, consistent with a slower moving ring. The R97 data is quite sparse for this galaxy, but seems to follow the general shape of our curve. The C06 H$\alpha$ curve somewhat follows the shape of our own save for the warp. As the C06 kinematics were determined using 3D velocity fields, it may be that we are instead dealing with a warp that requires a tilted-ring model to rectify. As we have used 2D spectra, we are not in a position to correct for such a warp. VCC692’s location within the cluster (0.5 Mpc away from M87) and its extreme bulk motion (C09) lead us to believe that it is falling into the cluster. It may be experiencing significant ram pressure stripping, which might explain the limited extent of our H$\alpha$ curve. Our
result $V_{\text{max}}^c = 53 \pm 3$ km s$^{-1}$ is almost exactly halfway between that of ALFALFA, $W_{50}^c/2 = 62$ km s$^{-1}$, and that of R97, $V_{\text{max}}^c = 44 \pm 13$ km s$^{-1}$.

**VCC768**: This galaxy is fairly inclined ($73^\circ$). The curve does not quite reach the flat regime, as it emulates solid-body rotation which is the signature of a dust plagued inclined system (Bosma et al. 1992). We do not have any additional RCs to compare our curve to, and our result $V_{\text{max}}^c = 84 \pm 2$ km s$^{-1}$ is smaller than F90’s HI linewdith, $W_{50}^c/2 = 102$ km s$^{-1}$.

**VCC801**: Here again, we find the R97 data to be quite sparse. On the other hand, the VIVA HI curve extends out to incredibly large radii and once again shows the unusual scooped shape. The VIVA collaboration describes it as being one of their most HI-rich galaxies (C09). The extent of our $H\alpha$ curve is matched by both of the other two $H\alpha$ surveys: R97 and C06. We find our result of $V_{\text{max}}^c$ to correspond with the available R97 and F90 results, within uncertainties.

**VCC809**: This edge-on galaxy follows solid-body rotation in our RC, and never quite reaches a flat plateau. A modelled fit could not be constrained. Our $V_{\text{max}}^c$ result is smaller than that of both HI surveys, ALFALFA and F90. They were most likely able to probe the full extent of the RC out to the flat regime since they did not have to worry about dust effects.

**VCC836**: The shape of our RC appears to greatly disagree with those of VIVA and R97 for this galaxy, yet our $V_{\text{max}}^c = 184 \pm 2$ km s$^{-1}$ result matches that of ALFALFA (186 km s$^{-1}$), R97 (202 km s$^{-1}$) and F90 (194 km s$^{-1}$) within uncertainties. It even matches the HI line width of 184 km s$^{-1}$ found in Hoffman et al. (1989). It may be that this galaxy is difficult to accurately extract an RC from: it is an edge-on Seyfert galaxy with a radio jet. VIVA found the HI content to be very deficient, truncated and asymmetric within the stellar disc (C09). Indeed, our curve does go beyond that of VIVA. C09 found no compelling evidence of
ram pressure effects in VCC836. Here again, small differences between the two observations may be due to differences in the rotation angle of the slit.

**VCC865**: The RC of this barless Sd galaxy shows very good correspondence with all our available comparison sources. The extent of our Hα curve is very similar to that of R97’s curve, whereas the VIVA curve extends nearly 2 $R_e$ farther out. In this case, it would appear that the HI gas has not been heavily stripped.

**VCC874**: This is an early-type spiral galaxy: an S0, or possibly an Sa. Subsequently, rotation is quite weak and may be hard to pin down. The HI gas appears to be rotating faster than the HII gas, but both our Hα curve and that of C06 match well. There is a non-trivial discrepancy between the HI surveys of ALFALFA (90 km s$^{-1}$) and F90 (53 km s$^{-1}$). Our result of 79 km s$^{-1}$ falls between these two.

**VCC912**: This galaxy shows a bump at approximately 1.5 $R_e$ on both sides, which would correspond to a faster rotating ring. There is also a large gap in the receding arm of the RC where Hα emission was not strong enough to accurately determine peaks. Due to these issues, no proper RC model could be fitted to the raw RC. That being said, our $V_{\text{max}}$ result matches that of ALFALFA very closely.

**VCC958**: The shape of our RC for this galaxy matches that of R97 well. VIVA’s HI curve follows our shape from -50$''$ to 0$, but shows some strange flaring at the end of each branch. Furthermore, our Hα curve extends out farther than VIVA’s HI curve, which may indicated HI gas stripping. Our $V_{\text{max}}$ result matches that of R97 quite well, but is nearly 90 and 60 km s$^{-1}$ greater than ALFALA and F90’s results, respectively. This issue has been addressed in C09; some HI is observed in absorption, and this absorbing gas has been redshifted by approximately 100 km s$^{-1}$ with respect to the nucleus. As both ALFALFA and F90 have made use of emission line widths, they have probably neglected the additional kinematic
component. We have also extracted a VDP for this galaxy.

**VCC980:** This Im galaxy is a disorganised system with weak rotation and large uncertainties. It could not be fitted with an RC model. We find good correspondence between our $V_{\text{max}}^c$ result and that of ALFALFA, but obtain a result twice as small as that of F90.

**VCC1003:** This galaxy is a barless S0 that shows the presence of a ring. It also contains a LINER. Its gas content is poorer than what is typically seen for RCs, which explains the very small extent of the curve. Nevertheless, the maximum rotational velocity is quite high. We have no other sources against which to compare. We have also extracted a VDP for this galaxy.

**VCC1126:** Our result for this barless Sb matches those of ALFALFA and F90 very well. We have also extracted a VDP for this galaxy.

**VCC1253:** This early-type barred galaxy shows both faint emission that is hard to correctly pin down in the RC and a very rapid rise associated to bars. Furthermore, it is classified as a Seyfert type 2. Our raw RC could not be modelled, and there are no external sources citing kinematic results. We have also extracted a VDP for this galaxy.

**VCC1379:** This is a weakly barred galaxy with an intermediate inclination of 58°. The extent of our Hα curve is less than that of C06’s. It may be that we did not choose a long enough exposure time for this galaxy. There appears to be a systematic offset between our curve and that of R97, although the extent of both curves is comparable. Our $V_{\text{max}}^c = 75 \pm 40$ km s$^{-1}$ result is slightly smaller than both R97 and F90’s results. We were incapable of fitting an RC model to our raw data. We suspect that we have not been able to capture the flat part of the RC and are thus coming short of the galaxy’s maximal rotational velocity.

**VCC1393:** The RC for this barred spiral does not reach its flat regime. Due
to this, we were not able to fit an RC model to our raw data and our $V_{\text{max}}^c$ result is shy of ALFALFA’s and F90’s by approximately 15 km s$^{-1}$. The large uncertainties on the end points of our curve indicate that we did not appropriately capture the emission in this galaxy, and it may require a second observation with a longer integration time.

**VCC1410**: Our $V_{\text{max}}^c = 95 \pm 21$ km s$^{-1}$ result for this late-type spiral matches F90’s result of 101 km s$^{-1}$ very well.

**VCC1486**: This galaxy is quite faint ($m_B = 15.4$). The flat regime of the RC is not reached. We obtained a $V_{\text{max}}^c$ result larger than that of ALFALFA, but consistent with that of F90 within uncertainties.

**VCC1508**: R97’s curve is extremely sparse for this bright barred late-type spiral, and is inconsistent with both our RC and that of C06. Between approximately 1.5 and 2.5 $R_e$, we find a large gap in the approaching arm of our RC. C06 bridges this gap, but the points contained within this area have very large uncertainties (at a level where we chose to reject our own data points). The rapid rise of the RC is consistent with a barred system.

**VCC1516**: The RC for this late-type spiral matches that of R97 very well except between -30$''$ and -50$''$. The 2D spectrum of this galaxy was visually inspected, and we do indeed see a small redward shift in the approaching arm’s emission line at this radius. It may be that a region of HII affected by non-circular motions is present. As R97’s data is quite sparse, and there is no data point between approximately -27$''$ and -41$''$, it may be that R97’s discarded any information in this region due to large uncertainties. Our $V_{\text{max}}^c$ result is slightly smaller than R97’s and F90’s. As this system is fairly edge-on, we have probably not reached the flattened part of our RC; note that the extent of our RC, although similar to R97’s, is less than 1 $R_e$. 


VCC1532: The extent of this galaxy’s RC is quite small, and we barely reach the flat regime. It was, however, modelled successfully and our $V_{\text{c max}}$ result is consistent with that of ALFALFA within uncertainties.

VCC1555: This bright late-type galaxy has a bar, and a steeply rising RC, signature of a bar. Since we have not reached the flat regime, no constrained RC model could be fitted. Again, we notice the strange scooped nature of the VIVA curve. We also see a dearth of H I signal near the centre of the galaxy where the stellar bar is present (C09). Our Hα curve does seem to terminate before that of R97 and C06. However, we do find our result to be consistent with that of F90. We do also note a discrepancy between R97 and C06.

VCC1566: This faint Sdm is a fairly disorganised system: data points beyond 0.5 $R_e$ are burdened by relatively large uncertainties, and the weak emission line shows little rotation. No model could be fitted.

VCC1588: This late-type spiral contains a weak bar, a weak ring and a LINER. While we did manage to fit an RC model, we see a large amount of flaring at the end of the approaching arm, which might indicate a warp in the disc. It may be that this complex system requires a tilted-ring model in order to accurately extract kinematics. We do however find a good correspondence for $V_{\text{c max}}$ between ALFALFA, 56 km s$^{-1}$ and us, 60 km s$^{-1}$.

VCC1811: The raw RC for this galaxy was successfully modelled, and all our results match very well with those of ALFALFA and F90.

VCC1859: C09 found the H I to be heavily stripped in this galaxy. They also found the Hα to be severely truncated within the stellar disc. Indeed, all plotted curves are very short. We do see an odd shape to R97’s curve; its extremely small extent and large uncertainties may indicate some flaw in their RC extraction. Our modelled RC fit seems to indicate that we have not yet reached the flattened part
of the curve. Extrapolating a $V_{\text{max}} = 92 \pm 9$ km s$^{-1}$, we exceed the results of ALFALFA and F90 by approximately 12 km s$^{-1}$. As these are both HI surveys, this may be due to the HI gas terminating long before the stellar disc. We have also extracted a VDP for this galaxy.

**VCC1929**: This galaxy has been classified as a Sdm. While it may seem that the RC has flattened out for this galaxy, a slight flare at the end of the receding arm, and the large uncertainties on the data points at both ends of the curve may lead us to believe otherwise. Both HI results of ALFALFA and F90 exceed our own by approximately 15 km s$^{-1}$. Whether this is due to a difference in HI and HII gas kinematics or due to the limited extent of our H$\alpha$ curve remains unclear.

**VCC1943**: This late-type spiral has been classified as a Seyfert, and is thought to contain both a weak ring and be weakly barred (see the curve’s steep rise). Beyond $0.5 R_e$, R97’s rotational velocities exceed both our own and that of C06. Both R97 and C06’s curves extents are much larger than our own curve’s. We were, however, able to successfully model our curve and our $V_{\text{max}}$ result matches that of ALFALFA and F90 perfectly.

**VCC1972**: This fairly inclined (76°) system is also quite faint ($m_B = 14.8$). Consequently, our H$\alpha$ curve does not extend very far out. R97’s curve seems to indicate larger rotation velocities, especially in the receding arm. Using our modelled RC to extrapolate a $V_{\text{max}}^c$, we find it to be consistent with ALFALFA, F90 and R97 within uncertainties. Unfortunately, we can visually see that R97 has reached its maximum rotational velocity before even $1 R_e$. The relatively large uncertainties on our last data points, especially in the approaching arm, lead us to believe that this galaxy may be worth re-observing with an increased integration time.

**VCC2023**: This is a fairly inclined (70°) barred system, and its extracted RC
has yet to flatten. Due to its larger inclination, we may be once more witnessing solid-body rotation due to dust effects. No modelled RC could be fit, and the $V_{\text{max}}^c$ result determined from the raw data leaves us short of ALFALFA and F90’s results by about 20 km s$^{-1}$. As these are HI surveys, they have most likely probed the whole disc, unobstructed by dust.

$VCC2058$: The H$\alpha$ RC for this late-type spiral containing a LINER falls well short of the HI curve. We see once more the odd scooped shape of the VIVA curve. ALFALFA and F90’s results are consistent with each other, but are both larger than our own $V_{\text{max}}^c$ result by approximately 25 km s$^{-1}$.

An issue with our H$\alpha$ RCs is their short extent. Comparing the extent of our H$\alpha$ RCs to that of their respective $i$-band light profile, our RCs extend out to roughly half of the light profile’s extent. While other H$\alpha$ surveys, such as R97 and C06, exhibit a similar pattern, we must determine if this is due to too short an integration time or a problem with our RC extraction algorithm. The latter would be unlikely though given that many of our optical RCs match other optical RCs well (such as those by R97 and C06) and even extend beyond HI RCs in some cases. Our software is therefore unlikely to artificially truncate our RCs short. Furthermore, visual examination of our spectra shows that RCs are typically extracted as far as the eye sees signal. We will be in a position to test if integration time is the culprit when we return to APO in January and February 2013 for three half-nights that were just awarded for this project. Our test will consist of re-observing a VCC galaxy for which the actual RC appears too shallow. We will double the integration time used in our previous measurement. Only then can we ascertain the true reason for the somewhat limited radial extent of our optical RCs.
5.5.2 Velocity Dispersion Profiles

Since we cannot conclude anything about the shape of our VDPs prior to correcting them for rotation, we will only comment on special cases found in our 33 gas-poor galaxies.

**VCC522**: We see a notable difference in the VDPs extracted from two separate observations of this ringed Sa galaxy. While we did manage to extract a profile both times, this galaxy is surely heavily affected by its rotation component. The $\sigma_o$ values are more consistent between the two observations than velocities measured at larger radii. Small differences in the alignment of the slit during observations may have caused a discrepancy between the two profiles. Once rotation has been eliminated, we may find the two profiles to match more closely.

**VCC570**: A very clean RC was extracted for this early-type spiral. It was found to have a $V_{\text{max}}^c = 131$ km s$^{-1}$, which is fairly large for an early-type spiral, reached a little bit short of $1 R_e$. Unsurprisingly, we find a rise in our VDP as well, finally maxing out at approximately $1 R_e$ with $120$ km s$^{-1}$. We anticipate the VDP for VCC570 to fall off quite quickly once the rotation component has been removed.

**VCC958**: Here again, a clean RC with $V_{\text{max}}^c = 180$ km s$^{-1}$ reached at $1.5 R_e$ has been extracted for this early-type spiral. We also see a rise and flattening of the VDP at $1.5 R_e$. Once more, we predict the VDP for VCC958 to decrease significantly once correction for rotation has been applied.

**VCC1003**: We have also extracted a RC for this S0 galaxy with $V_{\text{max}}^c = 293$ km s$^{-1}$ reached at $0.15 R_e$. It is interesting to note that its RC extends half as far as its VDP, although neither reach $1 R_e$. The VDP also peaks at $0.15 R_e$, but then falls off. This leads us to believe that the strongly rotating emitting HII gas is found only quite close to the core before being truncated.
**VCC1126:** The RC for this galaxy has not reached the flat regime. Nevertheless, we estimate a maximum velocity of $V_{\text{max}}^c = 88 \text{ km s}^{-1}$ reached at $0.18 \, R_e$. It may very well be the case that VCC1126’s rotational velocity increases beyond this point, however. This is supported by the fact that the VDP peaks and flattens at approximately $1.5 \, R_e$. Once rotation has been removed, we expect the VD results to decrease greatly.

**VCC1253:** While a RC was extracted for this S0 galaxy, it was quite disorganised and could not be modelled. The VDP does show a rise, but to a lesser degree than our other overlapping galaxies. While there is a clear rotation component in VCC1253, it is not as strong as in our other early-type spirals.

**VCC1859:** Strangely, both the RC and VDP for this galaxy show unusual jumps in velocity, although not at the same radius. Rotational velocity suddenly increases at $0.3-0.4 \, R_e$, whereas VD suddenly increases at $1 \, R_e$. It will be very interesting to see if correction for rotation removes the jump in the VDP, meaning it is purely a rotational phenomenon, or if it remains, which would imply something altogether different for the kinematics of VCC1859.

In general, we do find our VDPs do not intersect with the ACSVCS and HyperLeda results when they are available. However, we must emphasise that both these surveys have measured their VDs beyond the central point of the galaxy. At this radius, rotation is present. Once we have corrected for rotation, we anticipate most of our VDPs to decrease at large radii and intersect with the ACSVCS and HyperLeda values. For all 6 early-type galaxies that had both a RC and VDP available, we are pleased to see that both plots appear consistent with one another. When a clean RC is extracted, the VDP has a rising shape. This leads us to believe that our measurement technique for VDs is consistent with our measurement technique for rotational velocities.
Table 5.1: Rotational velocities measured at isophotal radii corresponding to 23 and 23.5 mag arcsec$^{-2}$. The rotational velocity $V_{\text{max}}$ was either taken to be the fit parameter $V_c$ from the multi-parameter function fit or the largest velocity found in the RC model, depending on the goodness of the function fit. All rotational velocities were corrected for inclination.

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<th>VCC</th>
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<th>$V_c$ (km s$^{-1}$)</th>
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<td>47 ±17</td>
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*Continued on next page*
Table 5.1 – Continued from previous page

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<th>VCC</th>
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Table 5.2: Rotational velocities interpolated from the multi-parameter function fit at isophotal radii corresponding to 23, 23.5, 24, 24.5, 25 and 25.5 mag arcsec$^{-2}$.

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Table 5.3: Linear fits for comparisons of rotational velocities with various galaxy samples, where $z_p$ is the zero-point intercept, $\rho$ is the correlation coefficient and $\sigma$ is the standard deviation.

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<th>Source</th>
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<th>$\rho$</th>
<th>$\sigma$ (km s$^{-1}$)</th>
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<td>$-8.0 \pm 0.2$</td>
<td>0.919</td>
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Table 5.4: Velocity dispersions as measured from our velocity dispersion profiles for smaller radii. The value of $\sigma_0$ is the $R = 0''$ intercept of a linear fit through the 4 smallest radial points of the dispersion profile. The first uncertainty corresponds to a 1-$\sigma$ uncertainty. The second cited uncertainty describes the range of possible results within the instrument's spectral resolution.

<table>
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<th>$\sigma_{\text{Re}/4}$ (km s$^{-1}$)</th>
<th>$\sigma_{\text{Re}/2}$ (km s$^{-1}$)</th>
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<td>198 ± 3 ± 0.9</td>
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Table 5.4 – Continued from previous page

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</tr>
<tr>
<td>1368</td>
<td>33 ±24 ±0.9</td>
<td>52 ±23 ±0.1</td>
<td>65 ±16 ±0.1</td>
<td>68 ±14 ±0.2</td>
<td>72 ±7 ±0.5</td>
</tr>
<tr>
<td>1412</td>
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<td>122 ±16 ±0.8</td>
<td>152 ±8 ±6</td>
<td>151.9 ±0.4 ±0.5</td>
<td>155 ±0.4 ±0.5</td>
</tr>
<tr>
<td>1479</td>
<td>45 ±3 ±2</td>
<td>47 ±2 ±1</td>
<td>47 ±1 ±1</td>
<td>50 ±0.8 ±1</td>
<td>53 ±0.6 ±1</td>
</tr>
<tr>
<td>1549</td>
<td>38 ±3 ±5</td>
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<td>37 ±5 ±4</td>
<td>38 ±3 ±4</td>
<td>40 ±3 ±4</td>
</tr>
<tr>
<td>1664</td>
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<td>186 ±1 ±0.7</td>
<td>186 ±0.9 ±0.7</td>
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<td>198 ±1 ±1</td>
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</tr>
<tr>
<td>1813</td>
<td>161 ±2 ±1</td>
<td>161 ±0.9 ±1</td>
<td>165 ±0.6 ±1</td>
<td>163 ±0.5 ±1</td>
<td>158 ±0.4 ±1</td>
</tr>
<tr>
<td>1859</td>
<td>82 ±3 ±2</td>
<td>84 ±2 ±1</td>
<td>85 ±2 ±1</td>
<td>84 ±2 ±1</td>
<td>85 ±1 ±1</td>
</tr>
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<td>1938</td>
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<td>225 ±2 ±0.5</td>
<td>225 ±1 ±0.5</td>
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<td>2092</td>
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<td>206 ±0.9 ±0.7</td>
<td>207 ±0.7 ±0.7</td>
<td>208 ±0.6 ±0.7</td>
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</table>

Table 5.5: Velocity dispersions as measured from our velocity dispersion profiles for larger radii. The first uncertainty is a 1-$\sigma$ uncertainty. The second uncertainty describes the range of possible results within the instrument’s spectral resolution. Missing values (--) indicate that the spatial axis of that galaxy’s spectra did not extend to a sufficiently large radius for the extraction of that velocity dispersion.

<table>
<thead>
<tr>
<th>VCC</th>
<th>$\sigma_{1.5Re}$ (km s$^{-1}$)</th>
<th>$\sigma_{2Re}$ (km s$^{-1}$)</th>
<th>$\sigma_{3Re}$ (km s$^{-1}$)</th>
<th>$\sigma_{4Re}$ (km s$^{-1}$)</th>
<th>$\sigma_{5Re}$ (km s$^{-1}$)</th>
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<tr>
<td>355</td>
<td>198 ±1 ±1</td>
<td>198 ±1 ±1</td>
<td>196 ±1 ±1</td>
<td>197 ±1 ±1</td>
<td>197 ±1 ±1</td>
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<tr>
<td>522 (Mar08)</td>
<td>62±0.8 ±2</td>
<td>64 ±0.8 ±2</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>522 (Feb12)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>570</td>
<td>119 ±0.9 ±0.9</td>
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<td>--</td>
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<td>--</td>
</tr>
<tr>
<td>654</td>
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Table 5.5 – Continued from previous page

<table>
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<tr>
<th>VCC</th>
<th>( \sigma_{1.5R_e} ) (km s(^{-1}))</th>
<th>( \sigma_{2R_e} ) (km s(^{-1}))</th>
<th>( \sigma_{3R_e} ) (km s(^{-1}))</th>
<th>( \sigma_{4R_e} ) (km s(^{-1}))</th>
<th>( \sigma_{5R_e} ) (km s(^{-1}))</th>
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<td>655</td>
<td>57 ± 2 ± 3</td>
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<td>147 ± 0.8 ± 0.5</td>
<td>147 ± 0.7 ± 0.5</td>
<td>148 ± 0.7 ± 0.5</td>
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<td>105 ± 1 ± 0.7</td>
<td>105 ± 2 ± 0.7</td>
<td>165 ± 2 ± 0.7</td>
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<tr>
<td>857</td>
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<tr>
<td>881</td>
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<td>1047</td>
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<td>105 ± 0.4 ± 0.6</td>
<td>105 ± 0.6 ± 6</td>
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<td>1126</td>
<td>88 ± 1 ± 0.8</td>
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<td>1154</td>
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<tr>
<td>1158 (Mar08)</td>
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<td>153.0 ± 0.3 ± 0.4</td>
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<tr>
<td>1158 (Feb12)</td>
<td>225 ± 0.5 ± 2</td>
<td>226 ± 0.5 ± 2</td>
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<tr>
<td>1231</td>
<td>243 ± 0.7 ± 0.7</td>
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<tr>
<td>1253</td>
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<td>–</td>
</tr>
<tr>
<td>1368</td>
<td>69 ± 11 ± 0.8</td>
<td>72 ± 10 ± 1</td>
<td>73 ± 29 ± 1</td>
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</tr>
<tr>
<td>1412</td>
<td>160.3 ± 0.4 ± 0.5</td>
<td>163.1 ± 0.3 ± 0.5</td>
<td>165 ± 0.4 ± 0.5</td>
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<tr>
<td>1479</td>
<td>55 ± 0.7 ± 1</td>
<td>55 ± 0.5 ± 1</td>
<td>54 ± 0.6 ± 1</td>
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<td>–</td>
</tr>
<tr>
<td>1549</td>
<td>40 ± 2 ± 4</td>
<td>39 ± 2 ± 4</td>
<td>43 ± 2 ± 4</td>
<td>38 ± 2 ± 4</td>
<td>37 ± 2 ± 4</td>
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<tr>
<td>1664</td>
<td>190 ± 0.6 ± 0.7</td>
<td>192 ± 0.5 ± 0.7</td>
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</tr>
<tr>
<td>1692</td>
<td>205 ± 0.8 ± 0.9</td>
<td>206 ± 0.7 ± 0.9</td>
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</tr>
<tr>
<td>1813</td>
<td>155 ± 0.3 ± 1</td>
<td>152 ± 0.3 ± 1</td>
<td>152 ± 0.3 ± 1</td>
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<td>–</td>
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<tr>
<td>1859</td>
<td>89 ± 0.9 ± 1</td>
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<td>–</td>
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<tr>
<td>1938</td>
<td>168 ± 0.4 ± 0.7</td>
<td>187 ± 187 ± 10</td>
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Continued on next page
Table 5.5 – Continued from previous page

<table>
<thead>
<tr>
<th>VCC</th>
<th>$\sigma_{1.5R_e}$ (km s$^{-1}$)</th>
<th>$\sigma_{2R_e}$ (km s$^{-1}$)</th>
<th>$\sigma_{3R_e}$ (km s$^{-1}$)</th>
<th>$\sigma_{4R_e}$ (km s$^{-1}$)</th>
<th>$\sigma_{5R_e}$ (km s$^{-1}$)</th>
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<td>1999</td>
<td>69 ± 0.7 ±1</td>
<td>70 ± 0.5 ±1</td>
<td>70 ± 0.5 ±1</td>
<td>70 ± 0.5 ±1</td>
<td>71 ± 0.4 ±1</td>
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<tr>
<td>2000</td>
<td>227 ± 0.7 ±0.5</td>
<td>228 ± 0.6 ±0.5</td>
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</tr>
<tr>
<td>2092</td>
<td>211 ± 0.5 ±0.7</td>
<td>212 ± 0.6 ±0.7</td>
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</table>
Table 5.6: Linear fits for comparisons of velocity dispersions with various galaxy samples, where $z_p$ is the zero-point intercept, $\rho$ is the correlation coefficient and $\sigma$ is the standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>$z_p$ (km s$^{-1}$)</th>
<th>$\rho$</th>
<th>$\sigma$ (km s$^{-1}$)</th>
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<tr>
<td>All Galaxies</td>
<td>2.57 ± 0.09</td>
<td>0.941</td>
<td>22.933</td>
</tr>
<tr>
<td>Galaxies w/ Emission</td>
<td>−6.3 ± 0.1</td>
<td>0.934</td>
<td>25.007</td>
</tr>
<tr>
<td>Galaxies w/out Emission</td>
<td>0.46 ± 0.04</td>
<td>0.951</td>
<td>19.192</td>
</tr>
<tr>
<td>ACSVCS</td>
<td>10.6 ± 0.1</td>
<td>0.974</td>
<td>15.453</td>
</tr>
</tbody>
</table>

Figure 5.1: Full rotation curve set stacked and colour-coded by magnitude.
Figure 5.2: Signal-to-noise ratio as a function of radius for all the galaxies retained for our velocity dispersion study. These are colour-coded by magnitude. The dashed line shows the $SNR$ cutoff level of 20/pixel. We observe a correlation between $SNR$ level and magnitude.
Figure 5.3: All the velocity dispersion profiles stacked onto each other and colour-coded by magnitude.
Figure 5.4: Comparison of our $V_{\text{max}}$ values corrected for inclination with analogs compiled by the ALFALA collaboration (in the radio), Fouqué et al. (1990) and Rubin’s team. No uncertainties were given for the Fouqué et al. values. The black dotted line traces the zero-point intercept.
Figure 5.5: Comparison between SHIVir velocity dispersions and those of other sources. Uncertainties were not plotted to keep the plot legible. The scale of the uncertainties differed from source to source. The black dotted line traces the zero-point intercept.

\[ \sigma = 22.9 \text{ km s}^{-1} \]
\[ zp = 2.57 \pm 0.09 \text{ km s}^{-1} \]
Figure 5.6: Comparisons between SHIVir velocity dispersions and that of other sources for both galaxies with and without significant nebular emission. Uncertainties were not plotted to keep the plots legible. The black dotted line traces the zero-point intercept.

(a) Galaxies shown to have significant nebular emission

(b) Galaxies shown to be free of significant nebular emission
Figure 5.7: Comparison of SHIVir and ACSVCS velocity dispersions over the same aperture. The black dotted line traces the zero-point intercept.
Figure 5.8: Velocity dispersion residuals as a function of the position angle residuals when comparing our work with the ACSVCS.
Chapter 6

Scaling Relations

Scaling relations are a foundation of extragalactic astronomy. As the study of galaxies can be most challenging, having a tool to infer certain immeasurable characteristics via other more readily observed quantities is invaluable. Here, we study scaling relations relating a property of the galaxy light with its dynamics (as an analog to mass). While certain relations may produce a tighter correlation than others, we seek the light-to-mass relations with tightest scatter. For late-type galaxies, we shall consider rotational velocities as the dynamical variable through variations of the TFR (TF77). For early-type galaxies, the dynamical variable of interest is the VD through the FJR (FJ76).

6.1 The Tully-Fisher Relation

The TFR holds true for rotationally supported galaxies. In its basic form,

\[ L \propto V^\alpha, \quad (6.1) \]

where \( L \) is a luminosity value, \( V \) is a rotational velocity and \( \alpha \) is a power index. The latter becomes a slope in log scale,
\[ \log(L) \propto \alpha \log(V). \]  

The light parameters tested in our study are $g - i$ colour, surface brightness $\Sigma$, the isophotal absolute magnitude $M_{23.5}$ and the total absolute magnitude $M_{\text{tot}}$. We opted to work in the $i$-band (rather than $g$ and $r$) to minimise dust extinction effects. In order to convert our apparent magnitudes to absolute values, we used either individual distances as measured by Blakeslee et al. (2009) using the SBF method, or assumed cluster membership and used the mean distance of 16.5 Mpc to the Virgo Cluster (Mei et al. 2007) when no individual distance was available. It should be noted that the intricate structure of the Virgo Cluster makes distance assignment a challenging and uncertain task (van den Bergh 1989).

For the dynamical variable, a possible free parameter is the radius at which the rotational velocity is measured. For instance, we can create different sets of TFRs using velocities extracted at different fiducial points (e.g. $V_{23}$, $V_{23.5}$ and $V_{\text{max}}$); the numbers refer to the surface brightness levels at 23 and 23.5 mag arcsec$^{-2}$. Figure 6.1 shows the TFRs constructed with those parameters. Matching TFRs based on our multi-parameter function fits (annotated with “mpf”) are found in Figure 6.2. In both figures, all the rotational velocities have been corrected for inclination. The correlation coefficient and standard deviation describing the scatter of each relation, as well as the estimated slopes and zero-points of each relation can be found in Table 6.1. The fits (here and forthcoming) use an orthogonal linear regression method.

We see that scaling relations based on isophotal markers ($V_{23}$ and $V_{23.5}$) do not fare well. Not only are they weakly populated, since most RCs do not extend beyond 23 mag arcsec$^{-2}$, they are also affected by large local errors. $V_{\text{max}}$ values yield slightly tighter TFRs but it is truly with the use of extrapolated velocities
taken from the multi-parameter function fit that we see the tightest correlations. We see an improvement on the order of 32% between local velocities taken from the data and velocities interpolated and extrapolated from our modelled curves. The TFR correlations appear slightly stronger at smaller radii, but only negligibly so. For the sake of the TFR, it would seem that a rotational velocity may be extracted at almost any radius as long as it is extrapolated from the RC modelling fit and that this model is well constrained. A potential future test might be to measure velocities at physically meaningful points, e.g. the turnover in the galaxy’s light profile.

Prior to this work, SHIVir colleague MM compiled rotational velocities for our SHIVir galaxies; those data, and their sources, are presented in Table 6.3. A total of 115 out of 286 galaxies have published velocities. Given the result from Table 6.1 that the scatter, correlation coefficient and relation parameters stay roughly the same no matter the radius at which \( V_{\text{rot}} \) is measured, we did not correct for any discrepancies in the methodology used in the literature values. Similarly, we found the TF parameter fits to be roughly the same whether \( M_{\text{tot}} \) or \( M_{23.5} \) was used. For the complete SHIVir TF plot in Figure 6.3, we have used \( M_{23.5} \). The black data points marked as “This Work” are \( V_{23.5} \) extrapolated from the RC model found in this thesis whenever such a model was successfully fit. If no such model could be determined, we selected the best equivalent rotational velocity from the raw RC data. All points have been colour-coded by their original source. Points from this work alone are best-fit by a linear regression (dashed black line) of slope \(-7.2 \pm 0.5\) and an intercept of \( M_i(2.3) = -21.5 \pm 1.1\) mag. Due to the compiled set being so much larger than this work’s subset, we may take the compiled data’s best-fit line (the dashed grey line) and that of the whole SHIVir body of work (the red dashed line) as both having a slope of \(-9.6 \pm 0.4\) and an intercept of \( M_i(2.3) = -22.4 \pm 0.8\)
It is clear that the scatter for the full SHIVir sample is much larger than that of this work alone. For one, the SHIVir data were collected from a heterogeneous group of datasets. Systematic biases between each dataset may be increasing the scatter. For example, the Gavazzi Hα subset seems to stand out most against the others; its TFR appears to have a shallower slope. While we do see the increase in scatter of the TFR at fainter magnitudes (especially in the regime where the baryonic TFR is expected to take over as explained in McGaugh et al. 2000), it seems like there is a great trough in the low-velocity/faint galaxy part of the plot. As we performed a magnitude-limited compilation of objects brighter than $m_{\text{photo}} = 16.5$, we will most likely need to correct for selection effects such as the Malmquist bias before inspecting the full TFR of the Virgo Cluster.

Many extensive TFRs exist (Geha et al. 2006; Masters et al. 2006; Courteau et al. 2007; Pizagno et al. 2007; Springob et al. 2007; Hall et al. 2012), sometimes anchored with calibrating galaxies (Kraan-Korteweg et al. 1988; Pierce & Tully 1992). The Virgo Cluster has also been widely used in the determination of multi-band TFRs due to its richness and proximity (Tully & Fisher 1977; Pierce & Tully 1988; Burnstein & Raychaudhury 1989; F90; Schöeniger & Sofue 1995; Yasuda et al. 1997; Toloba et al. 2011). It should be reiterated, however, that the Virgo Cluster is well-known for being dynamically active, unrelaxed and rife with complicated structure (Böhringer et al. 2004). Some discrepancies in the TFR parameters between galaxy samples may thus be expected.

We compare the TFRs determined for both our APO observations and the full SHIVir dataset (as explained in §6.1) in Figure 6.4. Velocities are corrected for inclination with a division by $\sin i$. We compare our TFRs to 6 other relations determined in the $i$-band. Our first conclusion is that our TFRs are consistent
with most other published TFRs within 1-σ. We find a very large scatter of 1.67 mag for our TFR based on the full SHIVir dataset and 0.85 mag for the TFR built with APO galaxies alone. The typical $i$-band TFR scatter has typically been found to be roughly 0.3-0.4 mag (Courteau et al. 2007; Hall et al. 2012) for field samples.

The reason for our larger TFR scatter may be explained by cluster dynamical effects, uncertain distances, and sample size bias. It is believe that most galaxy clusters span a radius of approximately one Abell radius $R_{\text{Abell}} = 1.5h^{-1}$ Mpc (Abell et al. 1989), which equals 2.14 Mpc assuming $h = 0.7$; here, $h$ is the Hubble constant. The size and exact shape of the Virgo Cluster remains however poorly defined. Some believe that spiral galaxies in the Virgo Cluster may be distributed in an elongated region which extends from 13 to 30 Mpc (Fukugita et al. 1993). Some of the very galaxies found in the SHIVir catalogue were determined to be at distances as large as 30.9 Mpc and as small as 10.9 Mpc by Blakeslee et al (2005). It would indeed appear that distance errors justify some of our large scatter. In Figure 6.5, we compute and plot the scatter based on distance errors alone assuming the following three scenarios: 1) plotted in blue, the Virgo Cluster spans 2 $R_{\text{Abell}}$ (resulting in distance errors on the level of 9%), is centred about a distance of 16.5 Mpc, and all SHIVir galaxies are found within, 2) plotted in orange, the Virgo Cluster is centred about a distance of 16.5 Mpc away, and distance errors are typically 15% (which is equivalent to ±2.48 Mpc), 3) plotted in red, the Virgo Cluster is centred about a distance of 18.0 Mpc away with a distance scatter of 3.9 Mpc (or typically 22%). This last scenario is based on the actual statistics determined from the distances used in this work. The resulting scatters derived from distance errors only were: 1) 0.18 mag, 2) 0.33 mag, 3) 0.46 mag. Recall that the total scatter we found on our best-fit TFR was 0.85 mag.
This includes distance errors, sampling effects and intrinsic scatter. If we remove the distance related scatter from our total measured scatter, we obtain a scatter of 0.71 mag, or an improvement of 16.5%. Distance uncertainties are clearly a non-trivial component of our TFR scatter.

The currently small size of our sample could also be a determinant factor. Indeed, increasing the sample size by a factor \( X \) should result in a scatter reduction by \( \sqrt{X} \) assuming purely Poissonian statistics and uncorrelated measurements. Given that the well-studied TFRs that we compare our own to are at least ten times larger than our own, we can anticipate scatter differences by at least factor of 3 or more. We tested this using the extensive TFR database of 3041 SDSS field and cluster galaxies by Hall et al. (2012). We selected random sub-samples that were ten times smaller than the parent sample. In all cases, the TFR scatter would be roughly twice higher for the smaller sample. The difference between the measured factor of 2 and the expected \( \sqrt{10} \) is simply due to correlated variables. Nonetheless, this test shows that the high scatter found in our sample is largely due to sampling uncertainties.

Increasing the sample size is one of our main goals. We are already planning another run at APO in January and February 2013 to observe another \( \sim 25 \) SHIVir spirals with missing or uncertain RCs. Distance errors will also be addressed via a new Bayesian study whereby galaxy distances can vary within the bounds of the Virgo Cluster. Using a flow model for the Virgo Cluster, we will quantify the fraction of the TFR scatter that is attributable to distance errors. This could not be completed on time for submission of this thesis.
6.1.1 Effect of Inclination Correction

Inclination corrections for disc galaxy observables (e.g. velocity, size, luminosity) have been notoriously challenging and ambiguous. This is in part due to the uncertain extinction effects by dust, ill-conceived notion of inclination (at what fiducial radius should it be measured?), and limited knowledge of the thickness of galaxy disks (inducing depth effects). Giovanelli et al. (1997) discuss such corrections including extinction effects. Inclination itself is typically derived from

$$\cos^2 i = \frac{(1 - e)^2 - q_0^2}{1 - q_0^2},$$  \hspace{1cm} (6.3)

where $q_0$ is the intrinsic axial ratio of the spiral disc. Estimates for $q_0$ are provided in Hall et al. (2012); we adopt their values here.

Ideally with light profiles, both radii and surface brightnesses should be corrected for inclination and extinction effects (Holmberg 1958). Unfortunately, the recipes by which surface brightnesses and radii are corrected are complex (e.g. Bottinelli et al. 1995). A first attempt is presented in Giovanelli et al. (1997) for the $i$-band whereby the observed projected radius, $R$, and its corrected version, $R'$, are related by:

$$R' = \frac{R_{\text{obs}}}{1 + 0.4\log(a/b)},$$  \hspace{1cm} (6.4)

where $a$ and $b$ are the semi-major and semi-minor axes of the outer disc respectively. Both these values have been determined by MM. Here, we see the interplay between the geometrical correction of inclination ($f(a/b)$) added to the dust extinction effects (factor in front of $a/b$). Were a disc galaxy completely transparent, we would expect isophotal radii estimates to decrease with inclination and surface brightness to increase with inclination. Conversely, a dusty galaxy will decrease in
surface brightness as inclination increases (Bosma et al. 1992). All these variables and assumptions added together can lead to an added uncertainty as large as 15 to 20% by correcting for inclination (Jacoby et al. 1992).

While our rotational velocities are all corrected for inclination, we investigate the effects of correcting our photometric observables for inclination as well. We compare the TF and Kormendy (luminosity as a function of radius) relations using corrected and uncorrected parameters. Note that any primed parameter (e.g. $M_{i,23.5}$, $V_{23.5}$) uses inclination-corrected isophotal radii, whereas velocity parameters with a single c subscripted have been derived from non-corrected isophotal radii, but have themselves been corrected for inclination. The Kormendy relations based on the galaxies with available RCs have been plotted in Figure 6.6. The fit parameters of both sample are consistent with each other within uncertainties, but we do notice a decrease of scatter by approximately 20% in the corrected sample. Similarly for the TFR in Figure 6.7, we find again that the fit parameters are consistent between the two samples, but scatter drops by 15% in the corrected sample. Thus correcting our isophotal radii for inclination does decrease the scatter of these relations by a non-negligible amount. An exact form of these corrections, and a discussion of their inherent uncertainties, will be provided in a forthcoming publication.

As our current galaxy sample is rather small, and we plan to continue on expanding our catalogue, we also investigate the role of sample size on the magnitude of our scaling relations’ scatter. Similarly to above, we compared the corrected and uncorrected Kormendy relations in Figure 6.8, but this time for all SHIVir galaxies with available light profiles. Again, we find the improvement in scatter for the corrected sample to be on the order of 20%. We also notice an improvement in the scatter of the Kormendy relation as we increase our sample size, but only
on the order of 5-10%.

6.2 The Faber-Jackson Relation

The analog of the TFR for pressure-supported galaxies is the FJR:

\[ L \propto \sigma^\alpha, \quad (6.5) \]

where \( L \) is a fiducial luminosity in some pre-determined bandpass, \( \sigma \) is a VD and \( \alpha \) is the power index. In log scale,

\[ \log(L) \propto \alpha \log(\sigma). \quad (6.6) \]

We measured VD using different apertures across the galaxy spectrum. We also interpolated VD using various fractions of each galaxy’s effective radius, \( R_e \), to determine which value would yield less scatter in its relation. Recall that values of \( R_e \) are drawn from YZ’s catalog. A central stellar VD \( \sigma_0 \), can also be extrapolated (rather than measured) to zero radius. It is thus prone to uncertainties given the extrapolation model. There appears to be no clear consensus in the literature for the “best” aperture to use. Many use apertures of \( R_e/8 \), \( R_e/4 \), or \( R_e \). Jorgensen et al. (1996) offer a first solid attempt to provide such a definition in the context of the Fundamental Plane. They corrected VDs to a circular aperture with a diameter of 1.19 \( h^{-1} \) kpc, or 3.4” at the distance of the Coma Cluster (99 Mpc). They did also use a circular aperture of diameter \( R_e/4 \) for comparison. While they did not study Virgo Cluster galaxies, their methodology has been applied by others (Gavazzi et al. 2003) to Virgo galaxies, among others. Needless to say, a physical aperture (in kpc) will sample different parts of a galaxy depending on its distance. A distance-independent metric might be more favourable to alleviate
such effects.

The LOSVD at different radii of a galaxy has been explored for single cases in the past (Franz & Illingworth 1988; Rix & White 1992; van der Marel & Franx 1993; van der Marel et al. 1994; Fisher et al. 1995; Statler & Smecker-Hane 1999; Battaglia et al. 2005; Dehnen et al. 2006; Walker et al. 2007; Brown et al. 2010), mostly in the context of new extraction techniques or kinematically peculiar galaxies, but not (as far as we know) in the context of a large galaxy survey such as SHIVir. There have been extensive VD measurements of cluster galaxies (e.g. Bender et al. 1994 for 44 bright elliptical galaxies; Mehlert et al. 2000 for 35 early-type Coma Cluster galaxies; Halliday et al. 2001 for 14 early-type galaxies, mostly in Virgo) but scaling relations were not studied. Furthermore, none seem to have tested apertures larger than $R_e$ as we do here. All FJ plots may be found in Figure 6.9 and 6.10. The estimated slopes, zero-points, and standard deviation for each relation can be found in Table 6.2.

It is clear that the FJRs seem to be more tightly constrained than the TFRs; the scatter of the FJRs are more than two times smaller than that of the TFRs. Measuring VD using a program such as pPXF appears to produce cleaner results than extracting rotation velocities from RC models, once confidence in the program is established. Interestingly, the correlation coefficients for the FJRs seem to peak with the use of $\sigma_{1.5r_e}$, which is beyond what other works in the literature use. As we increase the aperture up to $1 R_e$, we see a steady increase in the correlation and decrease in the scatter. We see the strongest relations for dispersions measured beyond $1 R_e$. This is consistent with what we see in Figure 5.2 where peak $SNR$ is reached between 1 and $2 R_e$ for most galaxies. It would thus make sense for the cleanest results to be extracted at these points, but many of our VDPs do not extend to such radii. In light of these results, we recommend the largest
possible aperture be used to measure VD while still producing reliable results for
the majority of our catalog. In our case, this would mean an aperture of 1.5 $R_e$.
Because we chose not to bin the spatial axis for most of the 2012 observations
to take advantage of favourable seeing conditions, we lost precious information at
larger radii. In other words, since the chip size remained the same but the spatial
dispersion was decreased, spectroscopy was only taken out to half the radius of
an unbinned observation. In the future, as we continue this work and extend our
survey, we will take care to extend the spatial axis to include larger fractions of
$R_e$.

Although exciting and promising, we must be cautious about concluding that
a larger aperture for VD extraction truly decreases the scatter of the FJR. We
emphasise that correction for rotation is imperative before any true conclusions
can be made. At larger radii, we observe less of the VD component and more of the
rotational component of our galaxies. This is especially true for the 6 early-type
spirals for which we have also extracted a RC. At these large radii, and without
having removed rotation, we are no longer investigating a pure FJR. Instead, we
are seeing a mixture of the FJ and TF relations. As the TFR is the fundamental
plane of spiral galaxies, whereas the FJR is not the fundamental plane of elliptical
galaxies, we expect the intrinsic scatter of the TFR to be smaller than that of the
FJR. It may be that the scatter of our FJRs with VDs measured at larger radii has
been falsely reduced due to the involvement of a TF component. Only correction
for rotation will allow us to see the whole picture clearly.

We may compare our Faber-Jackson relation with that of the ACSVCS collabora-
tion (Hašegan et al. 2005) where they adopt a slope of 0.25 (or $n = 4$) for giant
ellipticals in order to constrain their best-fit intercept, such that:
\[
\log \sigma_o = zp + 0.25 \log L_V. \tag{6.7}
\]

The FJR can ultimately be derived from the virial theorem, as would be expected for mostly relaxed systems such as elliptical galaxies:

\[
2K + U = 0, \tag{6.8}
\]

where \(K\) is kinetic energy and \(U\) is potential energy. Each is defined in a pressure-supported galaxy as:

\[
K = \frac{3M\sigma^2}{2}, \tag{6.9}
\]

\[
U \propto -\frac{GM^2}{R}, \tag{6.10}
\]

where \(M\) is the mass of the system, \(\sigma\) is the VD, \(G\) is the gravitational constant and \(R\) is the radius of the system. The resulting relation is

\[
L \propto \sigma^n, \tag{6.11}
\]

where \(n = 4\) (Bernardi et al. 2003). The power index (or slope value in log space) has actually been found to vary quite a bit. It was ultimately found to be \(n = 3.6 \pm 0.3\) by de Vaucouleurs and Olson (1982), but has been found to be as high as \(n = 7.8^{+1.9}_{-1.3}\) for SA0-bc galaxies. Outside of the Virgo Cluster, the FJ index has been found to vary slightly depending on waveband. Forbes & Ponman (1999) found a relation of \(L \propto \sigma^{3.92}\) for 229 early-type galaxies in the B-band, whereas Pahre et al. (1998) reported a relation of \(L \propto \sigma^{4.14\pm0.22}\) for 252 early-type galaxies in the K-band. Since the ACSVCS relation uses \(V\)-band magnitude, we may very
well expect our results to slightly differ from theirs. We compare our FJR with least scatter, $M_{23.5}$ as a function of $\log \sigma_{1.5re}$, in Figure 6.11. We include also the $L \propto \sigma^4$ line, zeroed to have the same $M_i(2.3)$ intercept as our own relation. Our FJR falls squarely within the expected range.

Dressler et al. (1987) elaborated on the relation between luminosity and VD for the Virgo Cluster, but also included the surface brightness parameter $\Sigma_e$, in order to study the Fundamental Plane. Although this thesis has focused on determining a best measure of the VD by minimizing the scatter of our FJR we will ultimately want to minimise the scatter of the FP. While the TFR is already the fundamental plane of spiral galaxies (Courteau & Rix 1999; Courteau et al. 2007; Dutton et al. 2007; Pizagno et al. 2007; Hall et al. 2012), the FJR is not. There have been a number of FP studies performed (Lucey et al. 1991; Gavazzi et al. 1999; Pahre et al. 1999; Sheth & Bernardi 2012), and we anticipate a smooth transition from our FJ analysis to an FP analysis for our 33 gas-poor galaxies. This will be included in our upcoming publication based on this thesis.
Table 6.1: Fit parameters of the Tully-Fisher plots, where $\alpha$ is the slope of the relation, $zp$ is the zero-point, $\rho$ is the correlation coefficient of the points and $\sigma$ is their standard deviation. The velocity values annotated with “mpf” were interpolated from our multi-parameter fits on the RCs. Rotational velocities have been corrected for inclination.

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Table 6.2: Fit parameters of the Faber-Jackson plots, where $\alpha$ is the slope of the relation, $zp$ is the zero-point, $\rho$ is the correlation coefficient of the points and $\sigma$ is their standard deviation.

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Figure 6.1: An array of Tully-Fisher type plots. The rotational velocities $V_{23}$ and $V_{23.5}$ were inferred from our observational data. The rotational velocities $V_{\text{max}}$ were either chosen as the largest RC model velocity or were the fitting parameter $V_c$ depending on how successful the multi-parameter function was in fitting the rotation curve.
Figure 6.2: An array of Tully-Fisher type plots. All rotational velocities were extrapolated using the multi-parameter fitting function.
Figure 6.3: Tully-Fisher plot of the best determined rotational velocities of this work compared to the values compiled for the SHIVir survey. The dashed lines are the best linear fits as determined by an orthogonal linear regression.
Figure 6.4: Our best Tully-Fisher relation ($M_{i, 23.5}$ vs $\log V_{c, 23}^e$) along with the sample’s best straight-line fit parameters drawn as a solid red line. The Tully-Fisher relation as determined by 6 other sources for cluster galaxies are also plotted for comparison. The statistical parameters cited pertain to the results from this work alone. The red dashed lines delineate the $1 - \sigma$ uncertainty region of our fit.
Figure 6.5: Effect of distance uncertainties on the scatter of our Tully-Fisher relation. The blue scatter assumes a cluster spanning $2 \, R_{\text{Abell}}$. The orange scatter assumes distance errors on the level of 15%. The red scatter is based off the statistics of the distance estimates used in this work.

\[
\begin{align*}
\alpha &= -7.2 +/- 0.5 \\
M_i(2.3) &= -21.5 +/- 1.1 \text{ mag} \\
\sigma &= 0.18 \text{ mag} \\
\sigma &= 0.33 \text{ mag} \\
\sigma &= 0.50 \text{ mag} \\
\sigma &= 0.85 \text{ mag}
\end{align*}
\]
Figure 6.6: Effects of inclination-correction on the Kormendy relation. Fit parameters, correlation coefficient, scatter and sample size have been included on each plot.
Figure 6.7: Effects of inclination-correction on the TFR. Fit parameters, correlation coefficient, scatter and sample size have been included on each plot.
(a) Full uncorrected Kormendy relation

(b) Full corrected Kormendy relation

Figure 6.8: Effects of inclination-correction on the Kormendy relation of all available SHIVir galaxies. Fit parameters, correlation coefficient, scatter and sample size have been included on each plot.
Figure 6.9: An array of Faber-Jackson type plots using velocity dispersions measured at smaller fractions of $R_e$. 
Figure 6.10: An array of Faber-Jackson type plots using velocity dispersions measured at larger fractions of $R_e$. 
Figure 6.11: Our best Faber-Jackson relation ($M_{23.5}$ vs $\log \sigma_{1.5Re}$) along with the sample’s best straight-line fit parameters. The red dashed lines delineate the $1 - \sigma$ uncertainty region of our fit. The black dash-dot line is the typically used $L \propto \sigma^4$ relation.

$\alpha = -4.3 \pm 0.2$
$zp = -11.0 \pm 0.4$ mag
$\rho = 0.86$
$\sigma = 0.37$ mag
Chapter 7

Summary & Conclusion

This work has provided a first analysis of the spectra acquired as part of the SHIVir survey over the last four years. Of all the 107 galaxies observed spectroscopically for SHIVir, spatially-resolved Hα RCs and VDPs were extracted for 34 gas-rich and 33 gas-poor systems respectively. 6 early-type spirals overlapped these two samples, as both a RC and a VDP were successfully extracted from them.

A significant part of this thesis has focused on the data reduction and analysis of optical spectra. The extraction of RCs for gas-rich systems was relatively straightforward in light of the high $S/N$ spectra available for such an analysis, and given that the extraction methods are already well documented (Courteau et al. 1992). A renewed aspect of our approach relied mostly on identifying the best definition of a rotational velocity in the context of Tully-Fisher analyses. Two quantities need to be examined simultaneously: a velocity, $V$, and a luminosity, $L$. Of the many tested values for $V$ and $L$, it was found that the specific definition of $V$ is inconsequential so long as it measured in a region of the model RC that is flat and so long as the corresponding luminosity is measured at the 23.5 mag arcsec$^{-2}$ isophote (in the $i$-band) or integrated over the whole surface brightness profile. Use of these $V$ and $L$ values would then result in the tightest TF relation. We stressed that the model RC yields a smoother TFR than using $V$ from the observed
RC. The improvement in scatter between these two methods (model vs observed RC) is 32%.

We were able to compare our RCs with those from the literature and found good agreement. We noticed the interesting result that a few HI RCs are shorter than their Hα counterpart (Koopmann et al. 2006; C09). This may be an indication of ram-pressure stripping by the intra-cluster medium. These seemingly “stripped” galaxies are on our list for a future multi-wavelength study of their structure and environment.

With scatters of 0.85 and 1.67 mag respectively, the TFRs that we find for our observed Virgo Cluster galaxies and all the SHIVir sample are clearly noisier than those published recently (e.g. Courteau et al. 2007, Saintonge & Spekkens 2011, Hall et al. 2012) for field galaxies. This result is slightly puzzling (especially given the general notion that field and cluster TFRs are rather similar). We did, however, find that the distance errors on the distance estimates used in our TFR study may contribute up to 16.5% of our scatter. To better address the source of the significant total scatter, a detailed study about distance errors and sampling effects as they pertain to our SHIVir survey will be needed. This will be done prior to final publication in a refereed astronomical journal. Additionally, we will also further investigate the full implications of applying corrections for inclination on our photometric parameters. While correcting for inclination does seem to reduce the scatter of our TFR, estimating inclination will itself add another large source of uncertainty to our work.

The reduction of stellar VDs was more challenging, both due to lower S/N spectra and the fact that methods for such reductions have been less well documented than for emission RCs. We developed a set of tools and guidelines for the reductions of absorption spectra and made use of the software pPXF for final
diagnostics. Needless to say, spectra were first de-redshifted into the rest frame of galaxy. Among our own guidelines, we have determined that long-slit spectroscopy with a $SNR$ below 20/pixel would yield unreliable VDs. Furthermore, the more extended the radial VDP, the better, in the sense that this enables a deeper exploration of the best dispersion value in the context of scaling relation analyses involving, e.g., the Faber-Jackson relation or Fundamental Plane. The accurate measurement of the instrumental resolution of the spectrograph as well as the choice of stellar templates, for comparison with the observed galaxy spectrum in order to recover the galaxy’s dispersion at a given radius, are also absolutely crucial. This statement cannot be overstated. We compared various choices of stellar templates and demonstrated their very significant impact on the final values of our VDs. We have also shown that a change of a few tenths of an angstrom in the spectral resolution of the instrument can result in up to 20% effects in the estimated VDs. Having converged on a set of final VDPs, we then identified the need to define a fiducial VD for each galaxy. A common definition is actually lacking in the literature, although many disparate definitions exist. Radial VDPs have been measured for decades now, but all to various depths. Given the reduced sensitivity of early detectors, initial profiles barely extended beyond 1 $R_e$ and most galaxy dispersions were naturally measured within fractions (e.g. 1/8, 1/4, 1/2) of an effective radius. With more modern detectors on 4-m class telescopes, like the ones we used, we can now routinely measure resolved dispersion profiles beyond 1-1.5 $R_e$. Indeed, we were able to show that the best VD which minimises the FJR is measured within a radius of 1.5 $R_e$. This is also consistent with our observation that the $SNR$ peaks at approximately 1.5 to 2 $R_e$.

The final selection of a “best” VD must however be tempered by the fact that our dispersion profiles (mashed over a pre-defined radial extent) have not yet been
corrected for rotation. It may be that the scatter of our FJRs measured within larger radii has been artificially decreased due to the TFR coming into play, as we have yet to remove the rotation component from our VDPs. We will also then be able to compare dispersions measured within an aperture versus those measured at that aperture. Furthermore, while our VD values compare well with those found in the literature, we suspect that the contribution of nebular emission in the spectral fitting of some of our galaxies may have been underestimated. Our future work will involve masking our SEDs for nebular emission prior to applying the pPXF algorithm. This also ought to alter our final dispersion profiles.

Another future investigation of ours will involve the definition of an ideal VD in the context of the Fundamental Plane (rather than the FJR). Time was simply lacking to enable this study, but it is high on our priority list.

Future telescope proposals will also focus on various key aspects of our SHVir survey that remain to be investigated, such as: a) can the scatter of the Virgo Cluster scaling relations (TF, FJ, FP) be reduced via improved sampling (through new measurements and/or more data from the literature) and better distances? b) can VDPs extending to 2, 3 or even higher fractions of $R_e$ yield tighter FJ/FP relations? c) will these extended dispersion profiles reveal a new manifold of galaxy structural parameters? and d) can we sample the velocity function to lower mass systems? As we expand our own data set, we will also make use of newly available data sets (VIVA; Toloba et al. 2011 and 2012, submitted) both to compare with our data and to expand upon our data using different observing passbands, galaxy types, etc.

Environmental factors are also most relevant for any study of cluster galaxies. We shall continue to collect environmentally-sensitive data (e.g. colours, multi-band luminosity and dynamical profile shapes, etc.) in our quest to understand
and differentiate the properties of cluster versus field galaxies. As we pursue our study of gas-poor and gas-rich galaxies in the Virgo Cluster, we also want to merge our velocity measures and combine our sample with other (e.g. HI) samples, to yield the most complete (multi-band) Virgo velocity function to date. Comparing such a function with predictions from theoretical models will prove an important step in galvanizing our belief in the currently favoured ΛCDM model.

Finally, it is hoped that this work will be a starting point for community-wide efforts to develop and implement rigorous and homogeneous methods in extracting internal galaxy dynamics. They are critical piece of the puzzle in our global understanding of galaxy formation and evolution. The author greatly aspires to remain a part of this grand dialogue.
Bibliography


van den Bergh, S. 1989, A&ARv, 1, 111.


Appendix A

Rotation Curves

Figure A.1: Rotation curve for VCC483 (taken in February 2009). The multi-parameter function fit is plotted as the magenta line.
Figure A.2: Rotation curve for VCC483. The multi-parameter function fit is plotted as the magenta line.
Figure A.3: Rotation curve for VCC559. The multi-parameter function fit is plotted as the magenta line. Rubin's data is plotted in red.
Figure A.4: Rotation curve for VCC570. The multi-parameter function fit is plotted as the magenta line.
Figure A.5: Rotation curve for VCC664. The multi-parameter function fit is plotted as the magenta line.
Figure A.6: Rotation curve for VCC692. The multi-parameter function fit is plotted as the magenta line. Rubin’s data is plotted in red.
Figure A.7: Rotation curve for VCC768. The multi-parameter function fit is plotted as the magenta line.
Figure A.8: Rotation curve for VCC801. The multi-parameter function fit is plotted as the magenta line.
Figure A.9: Rotation curve for VCC809. The muti-parameter function fit is plotted as the magenta line.
Figure A.10: Rotation curve for VCC836 (taken in February 2009). The multi-parameter function fit is plotted as the magenta line.
Figure A.11: Rotation curve for VCC836 (taken in April 2009). The multi-parameter function fit is plotted as the magenta line.
Figure A.12: Rotation curve for VCC865. The multi-parameter function fit is plotted as the magenta line.
Figure A.13: Rotation curve for VCC874. The multi-parameter function fit is plotted as the magenta line.
Figure A.14: Rotation curve for VCC912. The multi-parameter function fit is plotted as the magenta line.
Figure A.15: Rotation curve for VCC958. The multi-parameter function fit is plotted as the magenta line. Rubin’s data is plotted in red.
Figure A.16: Rotation curve for VCC980.
Figure A.17: Rotation curve for VCC1003. The multi-parameter function fit is plotted as the magenta line.
Figure A.18: Rotation curve for VCC1126. The multi-parameter function fit is plotted as the magenta line.
Figure A.19: Rotation curve for VCC1253. The multi-parameter function fit is plotted as the magenta line.
Figure A.20: Rotation curve for VCC1379.
Figure A.21: Rotation curve for VCC1393. The multi-parameter function fit is plotted as the magenta line.
Figure A.22: Rotation curve for VCC1410. The multi-parameter function fit is plotted as the magenta line.
Figure A.23: Rotation curve for VCC1486.
Figure A.24: Rotation curve for VCC1508. The multi-parameter function fit is plotted as the magenta line.
Figure A.25: Rotation curve for VCC1516. The muti-parameter function fit is plotted as the magenta line.
Figure A.26: Rotation curve for VCC1532. The multi-parameter function fit is plotted as the magenta line.
Figure A.27: Rotation curve for VCC1555. The multi-parameter function fit is plotted as the magenta line.
Figure A.28: Rotation curve for VCC1566. The multi-parameter function fit is plotted as the magenta line.
Figure A.29: Rotation curve for VCC1588.
Figure A.30: Rotation curve for VCC1811. The multi-parameter function fit is plotted as the magenta line.
Figure A.31: Rotation curve for VCC1859. The multi-parameter function fit is plotted as the magenta line.
Figure A.32: Rotation curve for VCC1929. The multi-parameter function fit is plotted as the magenta line.
Figure A.33: Rotation curve for VCC1943. The multi-parameter function fit is plotted as the magenta line.
Figure A.34: Rotation curve for VCC1972. The multi-parameter function fit is plotted as the magenta line.
Figure A.35: Rotation curve for VCC2023. The multi-parameter function fit is plotted as the magenta line.
Figure A.36: Rotation curve for VCC2058. The multi-parameter function fit is plotted as the blue dashed line.
Appendix B

Velocity Dispersion Profiles

Figure B.1: Velocity dispersion profile for VCC355. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.2: Velocity dispersion profile for VCC522 (taken in March 2008). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.3: Velocity dispersion profile for VCC522 (taken in February 2012). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.4: Velocity dispersion profile for VCC570. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.5: Velocity dispersion profile for VCC654. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.6: Velocity dispersion profile for VCC655. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.7: Velocity dispersion profile for VCC759. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.8: Velocity dispersion profile for VCC778. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.9: Velocity dispersion profile for VCC784. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.10: Velocity dispersion profile for VCC828. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.11: Velocity dispersion profile for VCC857. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.12: Velocity dispersion profile for VCC881. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.13: Velocity dispersion profile for VCC958. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.14: Velocity dispersion profile for VCC966. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.15: Velocity dispersion profile for VCC984 (taken in March 2008). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.16: Velocity dispersion profile for VCC984 (taken in February 2012). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.17: Velocity dispersion profile for VCC1003. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.18: Velocity dispersion profile for VCC1047. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.19: Velocity dispersion profile for VCC1126. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.20: Velocity dispersion profile for VCC1154. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.21: Velocity dispersion profile for VCC1158 (taken in March 2008). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.22: Velocity dispersion profile for VCC1158 (taken in February 2012). The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.23: Velocity dispersion profile for VCC1231. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.24: Velocity dispersion profile for VCC1253. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.25: Velocity dispersion profile for VCC1368. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.26: Velocity dispersion profile for VCC1412. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.27: Velocity dispersion profile for VCC1479. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.28: Velocity dispersion profile for VCC1664. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.29: Velocity dispersion profile for VCC1692. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.30: Velocity dispersion profile for VCC1813. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.31: Velocity dispersion profile for VCC1859. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.32: Velocity dispersion profile for VCC1938. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.33: Velocity dispersion profile for VCC1999. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.34: Velocity dispersion profile for VCC2000. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.
Figure B.35: Velocity dispersion profile for VCC2092. The yellow region highlights the possible range of values resulting from different assumed spectral resolutions as described in §4.2.