

Dark Haloes and the Kinematics of Disc Galaxies

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A thesis submitted for the degree of
Doctor of Philosophy of
The Australian National University



Australian
National
University

Research School of Astronomy & Astrophysics

Submitted: 6th June 2017

Approved: 26th October 2017

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Dedication

For Amma and Achan.

Declaration

This thesis is an account of the research undertaken between March 2013 and June 2017 at the Research School of Astronomy and Astrophysics, Faculty of Science, The Australian National University, Canberra, Australia. It has not been submitted in part or whole for any other degree at any other University.

This project was originally conceived as a project for the WiFeS spectrograph on the 2.3m telescope in Siding Spring Observatory to survey a sample of southern hemisphere spiral galaxies. The project was then broadened to include the Planetary Nebula Spectrograph (PN.S) collaboration after discussions between Ken Freeman, Ortwin Gerhard, and Magda Arnaboldi. The concept was presented to me in 2013, when I took it on as a PhD project. The original project has now expanded to include absorption line data from the VIRUS-W instrument in addition to the data from the PN.S for a sample of northern hemisphere spirals, as presented in this thesis. Complementary data from these two instruments proved to be an asset for putting our results on a firmer basis. My contribution to this project included:

- Prepared and submitted all the observing proposals for the VIRUS-W instrument, which included target selection and drafting an observing schedule for the run.
- Carried out all the observations using VIRUS-W between 2013 – 2015.
- Performed all the data reduction, management, and analysis for data from both instruments.
- Contributed towards setting up an $H\alpha$ reduction package for the PN.S.
- Wrote several python routines to perform the Gaussian two-component decomposition.
- Determined the best way to select the preferred model among the two and one-Gaussian fit using the Akaike Information Criterion and the Bayesian Information Criterion.
- Collated the best available literature values of surface brightness, scale length, and surface mass density of the gas in our target galaxies to determine its stellar mass-to-light ratio.
- Interpreted the results and led the efforts in the preparation of the papers.

I gratefully acknowledge the contributions of the members of our collaboration for this project:

- Magda Arnaboldi, Ortwin Gerhard, and Crescenzo Tortora for carrying out the observations on the PN.S between 2014 – 2015.
- Maximilian Fabricius for providing observing support on the VIRUS-W and training me to use the reduction pipeline 'CURE'.
- Lodovico Coccato for providing observing support on the PN.S and training me to use the PN.S reduction pipeline.
- Ken Freeman for determining the analytic solution to the effect of the cold layer on the equilibrium of the isothermal sheet, with inputs from Konrad Kuijken and Michael Merrifield.
- Magda Arnaboldi for helping setup an $H\alpha$ reduction pipeline and for determining the empirical relation to separate out HII region contaminants from PNe using the [OIII]- $H\alpha$ colour-magnitude diagram.
- Anastasia Ponomareva for carrying out all the rotation curve decompositions.
- Ken Freeman, Ortwin Gerhard, Magda Arnaboldi, Chris Flynn, Lodovico Coccato, Maximilian Fabricius, Michael Merrifield, Konrad Kuijken, and Anastasia Ponomareva for providing feedback and helpful discussions on the papers.

The chapters that appear in this thesis are modified forms of four papers. I am first author on three of these papers. The PN.S reduction techniques described in Chapter 3 will be part of a paper led by Magda Arnaboldi (PI of the PN.S collaboration), using the PN.S data for NGC 628 which I reduced and analysed.

The four papers that form part of this thesis are:

Chapter 2: Aniyan, S., Freeman, K. C., Gerhard, O. E., Arnaboldi, M., Flynn, C., 2016, "The influence of a kinematically cold young component on disc-halo decompositions in spiral galaxies: insights from solar neighbourhood K-giants", MNRAS 456, 1484-1494.

Chapter 3: Arnaboldi, M., Gerhard, O. E., Aniyan, S., Freeman, K. C., and the PN.S Consortium, "A dynamically cold and hot component in the Planetary Nebulae population of the spiral galaxy NGC 628 (M74)", to be submitted to A & A.

Chapter 4: Aniyan, S., Freeman, K. C., Arnaboldi, M., Gerhard, O. E., Coccato, L., Fabricius, M., Kuijken, K., Merrifield, M., 2017, "Resolving the Disc-Halo Degeneracy I: A Look at NGC 628", MNRAS, submitted.

Chapter 5 & 6: Aniyan, S., Freeman, K. C., Arnaboldi, M., Gerhard, O. E., Coccato, L., Fabricius, M., Kuijken, K., Merrifield, M., "Resolving the Disc-Halo Degeneracy II: NGC 6946 and M101" MNRAS, in preparation.

Suryashree Aniyan
June, 2017

Acknowledgements

Throughout this thesis, I use the pronoun 'we' rather than 'I' to describe various aspects of the research presented here. This is reflective of the truly collaborative nature of this work.

First and foremost, I would like to thank my supervisor, Ken Freeman, for his constant support during my PhD journey. Thank you for always being available to patiently answer all of my (often ridiculous) questions. You will always remain a role model in my career. It has been a pleasure working with you.

Thanks to my family for their continual support throughout my life. You always believed in me, even when I didn't.

I'd like to thank my co-supervisors Ortwin Gerhard and Magda Arnaboldi, especially for their guidance during the year I spent at ESO.

Thanks are also due to my collaborators Lodovico Coccato, Anastasia Ponomareva, Konrad Kuijken, Michael Merrifield, and the helpful staff at both ANU and ESO. They played a big part in bringing this project to fruition.

I'm grateful to the staff at the McDonald observatory and the Isaac Newton Group staff on La Palma for their support during my observing runs. Thank-you to the McDonald Observatory time allocation committee for their generous allocations of time on the 107-inch telescope. Special thanks to Maximilian Fabricius, Michael Opitsch, Karl Gebhardt, and Mike Williams for training me to use the VIRUS-W spectrograph.

I'm thankful for the ANU PhD scholarship, the ESO studentship, and the ARC Discovery Project grant DP150104129 that have supported me during my PhD candidature.

I'd like to thank all my friends, both in Munich and Canberra, for making this PhD journey fun. Isabella, Jeffrey, Wlady, Fan, Aki, Helga, Jane, Elise, Pete, Alessia, Haiyang, Manisha, and Anshu – you guys are awesome. Thanks Maise and Mia for being the best stressbusters on Stromlo.

Finally, but most importantly, thank you Karthick for your never-ending support in my pursuit of my goals. Thank you for always listening and never judging.

Abstract

The decomposition of the 21 cm rotation curve of galaxies into contribution from the disc and dark halo is challenging and depends on the adopted mass to light ratio (M/L) of the disc. There are several traditional methods of determining the stellar M/L but they remain uncertain. One method is the maximum disc hypothesis, where we adopt the largest M/L such that the disc's contribution to the observed rotation curve does not anywhere exceed the observed rotation curve. However, the maximality of the disc has not been conclusively proven. Another method used to estimate the M/L is from stellar population synthesis models, but these have significant assumptions involved such as the star formation history, the stellar initial mass function, chemical enrichment history etc.

A more direct way of calculating the stellar M/L is by measuring the surface mass density of the disc. For a given vertical density distribution, the Jean's equation in the vertical direction gives a rather simple relation between the disc surface mass density (Σ), vertical velocity dispersion (σ_z), and the scale height (h_z). Therefore, once we have adopted a density model for the disc, given the σ_z and h_z for a galaxy, we can determine the Σ . These densities can be used along with the surface brightness profile of the galaxy to determine the M/L . This is an observationally determined M/L without as many assumptions involved as in the other techniques.

Previous studies such as the DiskMass survey (Bershady et al. 2010a) and work by Herrmann et al. (2008) have used this method to conclude that galaxy discs are submaximal. The DiskMass survey used IFU spectroscopy and Herrmann et al. (2008) used planetary nebulae (PNe) to trace the kinematics of the discs of a sample of nearby spirals. Both these independent studies, using different tracers of the disc kinematics, concluded that galaxy discs are submaximal.

However, there is a conceptual problem that these studies were not able to address. Measuring the surface density of the disc requires a velocity dispersion and a disc scale height but they must be for the same population of the tracers. Discs of spirals contain stars (and PNe) of all ages. The younger stars (ages $\lesssim 3$ Gyr) have a relatively small scale height and velocity dispersion, compared to the older, kinematically hotter disc stars (ages $\sim 3 - 10$ Gyr). Since it is not possible to measure the scale height directly in face-on discs, we need to estimate it statistically using I-band and near-IR photometric data for edge-on galaxies; these estimates are weighted towards the scale height of the old disc, away from the dust plane of these galaxies. The spectra of the integrated light of the disc, which we use to measure the vertical velocity dispersion, come from the luminosity-weighted stellar population of the disc and contain a considerable contribution from the kinematically colder, younger disc population. Failing to separate out this younger component will lead to underestimating the velocity dispersion of the old disc. The surface density of the disc is therefore underestimated, and even if a disc is truly maximal disc, it will

appear to be submaximal.

In this thesis, we use a sample of K-giants in the solar neighbourhood to establish that there really do exist two thin disc components: a kinematically cold component with a small dispersion and a hotter component with about twice the dispersion. We establish that assuming a single kinematically homogeneous population of stars will underestimate the surface mass density by a factor of 2. This factor will play a huge factor in whether a galaxy is classified as being maximal or submaximal.

We then use a sample of three nearby, relatively face-on spirals (NGC 628, NGC 6946, and NGC 5457) to extract the vertical velocity dispersion of the hot thin disc. We use absorption line spectra from the VIRUS-W instrument at McDonald observatory and PNe observed with the Planetary Nebula Spectrograph to trace the kinematics of the discs of these galaxies. In all three galaxies, using these two kinematic tracers, we were able to extract the velocity dispersion of the hot component, which we then used along with the scale height (for the same component) to determine the surface mass densities. The central surface mass densities that we derive are typically at least a factor of 2 higher than previous studies. We find that the vertical velocity dispersion of the hot component falls exponentially with twice the radial scale length of the galaxy as a function of radius. This implies that these galaxies have a constant scale height and constant M/L . We used available photometric data to calculate the M/L in each radial bin where we determined the dynamical surface densities. We believe that this is the first dynamical study that gives the observed M/L in different radial bins for these nearby disc galaxies.

We find all three of our analysed galaxies to be maximal. The baryons dominate in the inner parts of these galaxies, with the dark halo contributing minimally to the rotation curve.

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INTRODUCTION

The radial component of the gravitational field in the outer parts of spiral galaxies is known to be dominated by their massive dark haloes. However, the nature of dark matter remains a mystery. Several strides have been made in the field of astronomy to try and understand the properties of dark haloes of galaxies. Since dark matter does not interact with light like baryonic matter, HI rotation curves are currently the best method to measure parameters for dark haloes of spiral galaxies, such as their typical scale densities and scale lengths. These quantities are interesting in themselves but they are also cosmologically significant, because the densities and scale radii of dark haloes follow well-defined scaling laws which can be used to measure the redshift of assembly of haloes of different masses (Kormendy & Freeman 2016; Macciò et al. 2013).

Fig. 1.1 show the results from Kormendy & Freeman (2016), which demonstrates the constancy of the product of $\rho_0 r_c$ of dark matter as a function of the observed absolute magnitudes of galaxies with different morphologies and Hubble types, where ρ_0 is the central densities and r_c is the core radii of the dark haloes. Kormendy & Freeman (2016) show that DM haloes in less luminous galaxies have smaller core radii, higher central densities, and smaller central velocity dispersions (σ). Fig. 1.2 shows the correlations between halo r_c , ρ_0 , and σ and galaxy absolute magnitude M_B from Kormendy & Freeman (2016).

For a bulgeless disc galaxy, the density profiles of the dark haloes of spiral galaxies can be measured by decomposing their 21-cm rotation curves into the contributions from the exponential disc and the dark halo. For an infinitely-thin exponential disc, the surface mass density at a particular radius, $\Sigma(R)$, can be written as:

$$\Sigma(R) = \Sigma_0 \exp(-R/h_R) \quad (1.1)$$

where, Σ_0 is the central surface mass density of the disc and h_R is the radial exponential scale length. The total mass within the radius can then be expressed as:

$$M(R) = 2\pi \int \Sigma(R)R \, dR = 2\pi\Sigma_0 h_R^2 [1 - \exp(-R/h_R)(1 + R/h_R)]$$

As shown in Freeman (1970) the above equation gives the potential ϕ :

$$\phi(R) = -\pi G \Sigma_0 R [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

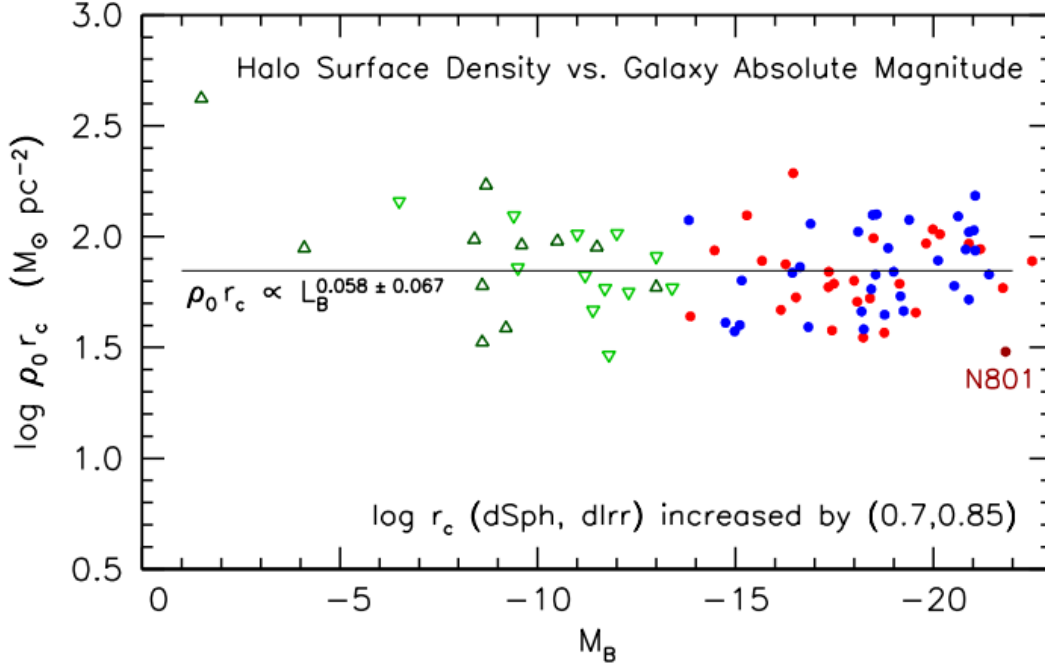


Figure 1.1: The product $\rho_0 r_c \propto$ surface density of dark haloes as a function of observed absolute magnitude. The results derived using isothermal haloes in rotation curve decompositions of Sc - Im galaxies are shown as blue points. The red points show results derived using pseudo-isothermal halo models. The straight line shows the near constant surface density for the Sc - Im galaxies. The dark and light green points are for dSph and dIm galaxies. The $\log r_c$ values for their dark haloes are derived from the $\log r_c$ values for their stellar or HI distributions as mentioned in the plot. See Kormendy & Freeman (2016) for more details.

where $y = r/h_R$ and I, K are modified Bessel functions. The circular velocity V_{rot} of the disc then becomes:

$$V_{rot}^2(R) = R d\phi/dR = 4\pi G \Sigma_0 h_{RY}^2 [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

When fitting observed rotation curves with disc + dark halo models, the scale length h_R is known from surface photometry, but the central surface density $\Sigma(0)$ is usually not known and needs to be determined somehow. The remaining gravitational field is then attributed to the dark halo. Hence the surface density scaling of the disc is important to understand the properties of the dark halo.

Typically, in the decomposition process, the shape of the disc's contribution to the rotation curve is scaled from its surface photometry according to the adopted mass-to-light ratio (M/L) of the disc. For the solar neighbourhood, the M/L values for the solar neighbourhood can be determined directly from star counts: e.g. Just et al. (2015) for the near IR and Flynn et al. (2006) for optical bands. They find $M/L \sim 1.5, 1.2$ and 0.34 (M/L) $_{\odot}$ in the V, I and K-band respectively. These values cannot be universally applied to other Galactic regions and other discs because M/L depends on the local star formation history. We need to find an independent way

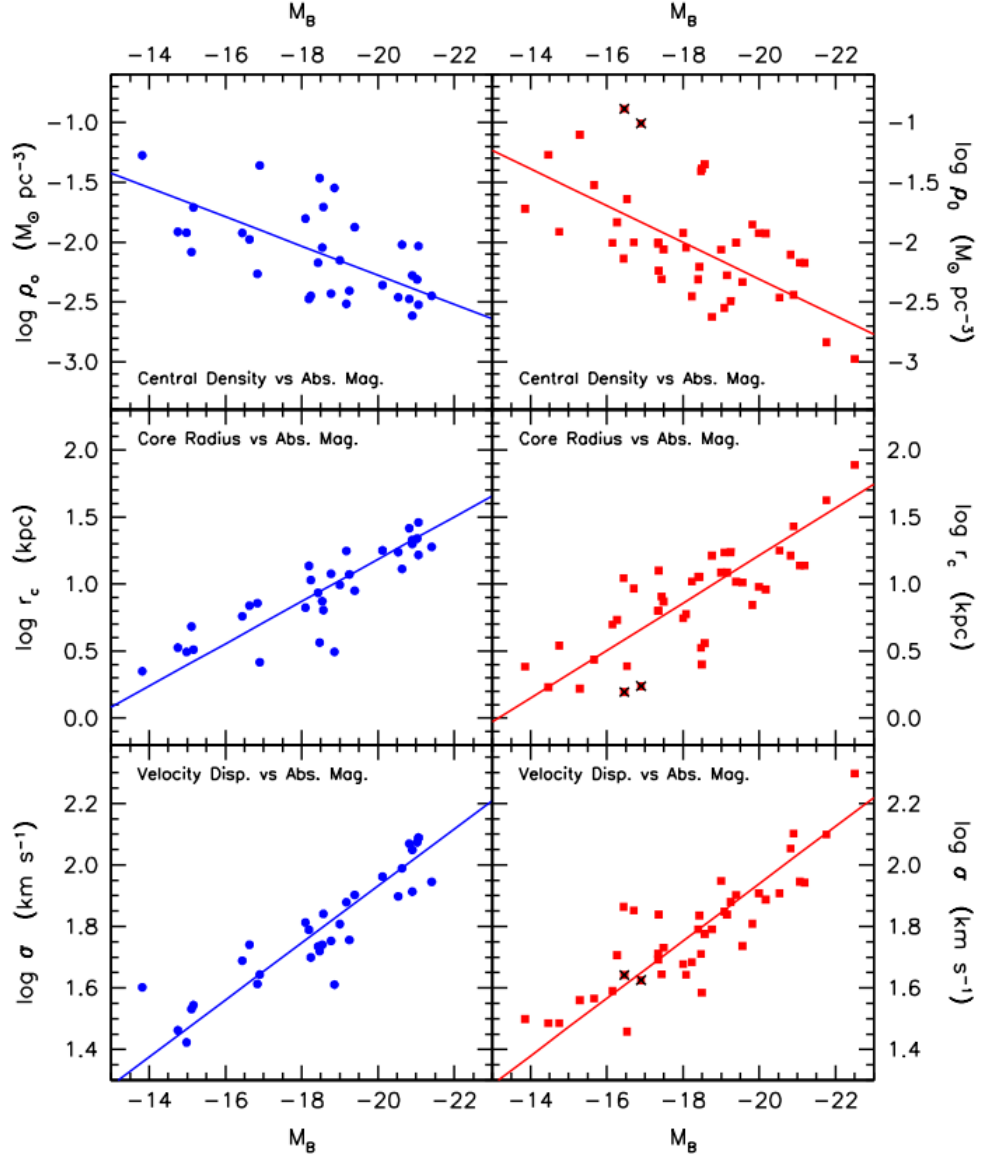


Figure 1.2: Correlations of dark matter central density ρ_0 (top panels), core radius r_c (middle), and particle velocity dispersion σ (bottom) with galaxy absolute magnitude M_B . The left panels show results derived using isothermal halos in the rotation curve decompositions of Sc Im galaxies. The right panels show results (red points) derived using pseudo-isothermal halo models. See Kormendy & Freeman (2016) for more details.

to estimate the surface density of the disc.

1.1 Disc-Halo Degeneracy

The stellar M/L values for external discs are still uncertain. As the adopted M/L of the disc is increased, the disc contributes increasingly more to the rotation curve, and the resulting halo becomes less dense and has a longer scale length (see Fig. 1.3). The adopted M/L for the disc is critical to the outcome. The M/L can be estimated from the rotation curve itself, but this suffers from the well-known degeneracy between the contributions from the disc and the dark halo (van Albada et al. 1985). Some methods to overcome this 'Disc-Halo degeneracy' are discussed in the following sections.

1.1.1 Maximum Disc Hypothesis

An often used method to break the disc-halo degeneracy is the maximum disc hypothesis where the disc contribution to a galaxy's rotation curve is maximized in the sense that the amplitude of the disc-alone rotation curve is made as large as the observations allow (van der Kruit & Freeman 2011). We do not know if this is correct. It may overestimate the contribution of the disc to the rotation curve while underestimating the contribution of the dark halo. In maximum disc decompositions, the disc mass provides $85\% \pm 10\%$ of the observed rotational velocity at 2.2 scale lengths, which is where the exponential disc peaks (Sackett 1997). This hypothesis remains unproven. The lack of dependence of the residuals of the Tully-Fisher (TF) relation on surface brightness is evidence to the contrary (Courteau et al. 2003), but most numerical studies of gas flow and bar evolution in spirals support the maximum disc hypothesis (see Sellwood 2014 for a review on the subject). Fig. 1.3 illustrates an example of using maximum-disc hypothesis to decompose the observed rotation curve of the galaxy NGC 3198 (left panel) and a decomposition that has maximum contribution from the halo and minimum contribution from the disc (right panel).

Kormendy & Freeman (2016) assume a maximal disc in their analysis. For a power spectrum of initial density fluctuations that is a power law in wavenumber k , $|\delta_k| \propto k^n$ (Djorgovski 1992). Djorgovski (1992) showed that the correlations shown in Fig 1.2 between ρ_o , r_c and σ depend on the index n . The Λ CDM theory predicts $n \sim -2.1$ at a halo mass of $10^{12} M_\odot$ (Shapiro & Iliev 2002). Kormendy & Freeman (2016) find a value of $n = -2.0 \pm 0.1$ from the observed correlations, using a maximal disc and an isothermal halo, which is remarkably close to the predicted value. Alternately, maximum disc decompositions performed by Martinsson et al. (2013a) using an NFW density profile for the dark halo, results in halo parameters that are inconsistent with the results of simulations. Sub-maximal disc decompositions, however, yield halo parameters that are consistent with Λ CDM simulations.

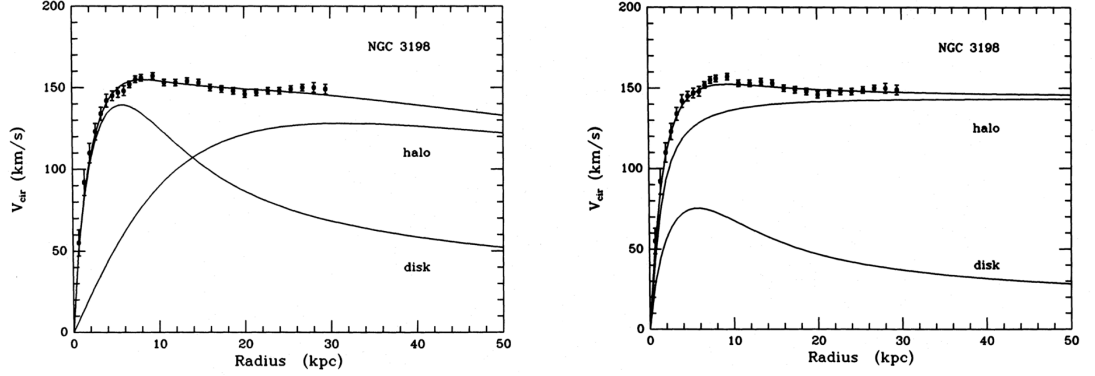


Figure 1.3: An image from van Albada et al. (1985) illustrating the rotation curve decomposition for NGC 3198 using (a) a maximum disc, and (b) a minimum disc.

1.1.2 Stellar Population Synthesis Models

Stellar population synthesis (SPS) models were developed to model the spectral energy distributions of galaxies, that relied on stellar evolution theory to constrain the range of possible stellar types at a given age and metallicity (see for eg. Bruzual & Charlot 2003, Conroy 2013, Courteau et al. 2014). The simple stellar population (SSP) is defined as a group of coeval stars with homogeneous chemistry (at birth) and similar orbits/kinematics (Courteau et al. 2014). A galaxy can be considered to be the sum of all present SSPs. The main unknown of an SSP is the stellar Initial Mass Function (IMF), which gives the mass spectrum of the stellar generation at birth. The distribution of stellar generations in time and chemical enrichment is called the Star Formation History (SFH). Several analytical laws describe plausible SFHs which depend on the timescale of the Star Formation Rate (SFR) (Courteau et al. 2014). Stellar evolutionary models are, usually, made use of in modelling a galaxy spectrum. Integrated spectra for galaxies are calculated by adding up the contributions of the individual model stars after assuming an IMF and a SFH. These evolutionary population synthesis (EPS) models are dependent on five key parameters – the age of the population, SFH, metallicity, chemical abundance ratios, and the IMF. EPS models calculate the total stellar mass content (M_*) and luminosity (L_*) by making use of the stellar evolutionary tracks and/or isochrones, empirical or theoretical stellar spectral libraries, and the parametrization for the mass-loss which affects several late stages of evolution such as the Thermally-Pulsing Asymptotic Giant Branch (TP-AGB), the Red Giant Branch (RGB), the Horizontal Branch (HB), and also the Main Sequence (MS) in young populations (Courteau et al. 2014). Thus, the stellar M_*/L_* can in principle be estimated from SPS models (e.g. Bell & de Jong 2001). However, these values remain insecure because of the several significant assumptions that go in to these models – such as the star formation and chemical enrichment history, the stellar IMF, accurate accounting of late phases of stellar evolution (e.g. Maraston 2005) and the internal dust absorption (Tully & Fouqué 1985).

1.1.3 Measuring the Surface Mass Density

To break the disc-halo degeneracy, the vertical velocity dispersion of stars in the discs can be used to measure the surface mass density of the disc (e.g. Bottema 1997, Herrmann et al. 2008, Bershady et al. 2010a). The Poisson equation for the case of axial symmetry is:

$$\frac{\partial K_R}{\partial R} + \frac{K_R}{R} + \frac{\partial K_z}{\partial z} = -4\pi G\rho(R, z) \quad (1.2)$$

where K_R and K_z are the gravitational force components, z is the vertical height, R is the radial distance, G is the gravitational constant, and ρ is the density. From Oort (1965), we know that at small z ,

$$\frac{\partial K_R}{\partial R} + \frac{K_R}{R} = 2(A - B)(A + B) \quad (1.3)$$

where A and B are Oort constants. Eqn. 1.3 becomes equal to zero for the flat part of the rotation curve. Eqn. 1.2 can then be written as:

$$\frac{\partial K_z}{\partial z} = -4\pi G\rho(z) \quad (1.4)$$

This is the plane-parallel case, and flat rotation curves do make this an excellent approximation at low z (van der Kruit & Freeman 1986). The Jeans equation then becomes

$$\frac{d}{dz}[\rho(z)\sigma_z^2(z)] = \rho(z)K_z \quad (1.5)$$

Combining the above equations (see van der Kruit 1988 for details) gives:

$$\Sigma = f\sigma_z^2/Gh_z \quad (1.6)$$

where σ_z is the vertical velocity dispersion (integrated vertically through the disc), G is the gravitational constant, h_z is the scale height and f is a geometric factor that depends weakly on the adopted vertical structure of the disc. h_z can be the exponential scale height when the vertical density of the disc is assumed to be exponential i.e $\rho(z) \propto \exp(-z/h_z)$ or the exponential scale height at large z when the vertical density of the disc is assumed to follow a *sech*² model: $\rho(z) \propto \text{sech}^2(z/2h_z)$. The surface brightness of the disc and the surface mass density (Σ from Eqn. 1.6) together give the M/L of the disc. The factor $f = 2/3\pi$ for a vertically exponential disc, and $f = 1/2\pi$ for a vertically isothermal disc (van der Kruit & Freeman 2011). The velocity dispersion σ_z is measured from spectra of the integrated light of the disc in relatively face-on galaxies. These observations are difficult because high resolution spectra of low surface brightness discs are required to measure the small dispersions (for the old disc near the sun, $\sigma_z \sim 20 \text{ km s}^{-1}$). The other parameter, the disc scale height h_z , is typically about 250 pc, but cannot be measured directly for these face-on galaxies. It has to be estimated statistically from similar galaxies, seen edge-on, using the relation between scale height and absolute magnitude or

circular velocity that has been measured for samples of edge-on galaxies. Yoachim & Dalcanton (2006) show the correlation of the scale heights of the thin and thick disc with circular velocity of edge-on disc galaxies using R-band data. Similarly, Kregel et al. (2005) did I-band studies of edge-on disc galaxies and show correlations between the scale height and intrinsic properties of the galaxy such as its surface brightness. van der Kruit & Freeman (1984), Bottema et al. (1987) and Bershadsky et al. (2010a) have used this method and find that the disc M/L is relatively low and the discs are submaximal¹. Bershadsky et al. (2011) find that the dynamical stellar M/L obtained is about 3 times lower than the M/L from maximum disc hypothesis. The following section discusses some important results from some of these previous studies that have used this method to resolve the disc-halo degeneracy.

1.2 Earlier Studies

1.2.1 Work by van der Kruit & Freeman

One of the first papers that used vertical dynamics to establish the submaximality of galactic discs is the work by van der Kruit & Freeman (1984). This work looked at two face-on spiral galaxies – NGC 628 and NGC 1566 using long slit spectra from the Boller and Chiven spectrograph on the 74 inch telescope at Mount Stromlo Observatory. They summed up all pixels containing interarm data to build up the signal. They then used the power spectrum method (see Illingworth & Freeman 1974) to compare the power spectrum of the galaxies with the power spectrum of K-giant template stars convolved with different Gaussian broadening functions to determine the best estimate of the vertical velocity dispersions. They find σ_z values of $60 \pm 20 \text{ km s}^{-1}$ and $80 \pm 15 \text{ km s}^{-1}$ for NGC 628 and NGC 1566 respectively, at a radial distance of one luminosity scale length. These values suggest a $(M/L)_B \sim 5 - 10 (M_\odot/L_\odot)_B$. These values indicate that more than 50% of the mass within the optical radius comes from the dark halo. This study, therefore, concluded that these galaxy discs are submaximal.

1.2.2 Work by Bottema

Following the work by van der Kruit & Freeman (1984), the next key research in this field was a series of papers by Bottema et al. (1987); Bottema (1989b,a, 1993). Bottema (1993) summarised the results of a sample of 12 spiral galaxies (including data for the Milky Way from Lewis & Freeman 1989). This work concluded that the velocity dispersion exponentially declines as a function of radius, consistent with a constant thickness, constant M/L . This study also finds that, over the luminosity range of the observed galaxies, the ratio of the vertical velocity dispersion to the radial velocity dispersion is a constant ~ 0.6 . This is consistent with the value obtained from studies of stars in the solar neighbourhood. Based on the sample of

¹A maximal disc has the maximum M/L value consistent with the observed rotation curve and a non-hollow dark halo. Typically, the disc of a maximal disc provides about 85% of the rotational velocity at the peak of the rotation curve (Sackett 1997).

12 galaxies, this study also finds that the maximum rotation supplied by a disc is (on average) only $\sim 63\%$ of the observed maximum rotation, roughly independent of the size of the galaxy. This implies that galactic discs are mostly submaximal. Fig. 1.4 shows the velocity dispersion of the sample of galaxies as a function of rotational velocity of the galaxy.

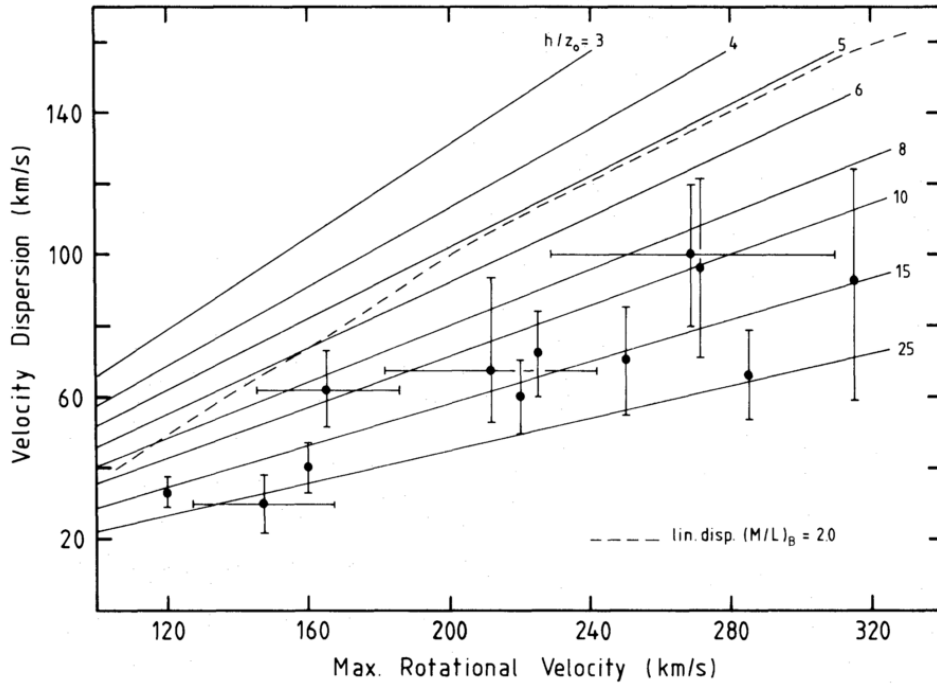


Figure 1.4: Results from Bottema (1993) that shows the velocity dispersion as a function of the maximum rotational velocity for the sample of galaxies. h/z_0 is the ratio of the scale height to the thickness of the disc. For realistic values of h/z_0 , the curves lie above the data. The dashed line indicates the dispersion vs. rotational velocity relation for a galaxy with $M/L = 2$ in the B-band. For this sample of galaxies, the disc only contributes on average $\sim 63\%$ to the observed rotation, suggesting a submaximal disc.

1.2.3 Work by Herrmann & Ciardullo

The works described in sections 1.2.1 and 1.2.2 used integrated light studies to check for disc maximality. However, these studies only looked at the inner regions of the disc, due to signal-to-noise limitations. Herrmann et al. (2008) used planetary nebulae (PNe) as dynamical tracers to calculate the surface mass density. This method allowed them to measure the σ_z out to a large radial extent, typically > 4 scale lengths. This is useful for studying the radial change in σ_z in galaxies. From Eqn. 1.6, the vertical velocity dispersion is:

$$\sigma_z(r) \propto \sqrt{\Sigma(r)h_z}$$

Substituting Eqn. 1.1 in the above equation gives:

$$\sigma_z(r) \propto \sqrt{\Sigma_0 \exp(-r/h_R) h_z}$$

where h_R and h_z are the scale length and scale height of the galaxy respectively and Σ_0 is the central surface mass density of the disc. Assuming a constant M/L and constant scale height for the disc, we expect the σ_z to fall exponentially with twice the galaxy's scale length:

$$\sigma_z(r) \propto \exp(-r/2h_R)$$

Herrmann et al. (2008) and Herrmann & Ciardullo (2009a,b) observed 5 nearby face-on spiral galaxies – IC 342, M74 (NGC 628), M83 (NGC 5236), M94 (NGC 4736), and M101 (NGC 5457), using planetary nebulae as tracers. PNe are part of the post-main-sequence evolution of most stars with masses in the range 0.8 to 8 $M_\odot$. Up to 15% of the flux from the central stars of PNe is reprocessed into the [OIII] emission line at 5007 Å (Dopita et al. 1992). These objects are plentiful in stellar populations with ages between 0.1 and 10 Gyr. These properties make PNe useful probes of the internal kinematics of galaxies. They can be detected in galaxies out to many Mpc. They are easier to detect at large galactocentric radii where the background continuum is fainter, and are therefore an important complement to integrated light absorption-line studies. PNe allow the measurement of stellar kinematics to be extended out to typically (4-5) R_e (Douglas et al. 2002).

Herrmann et al. (2008) surveyed their galaxies for PNe with on-band/off-band [OIII] and H α imaging with the WIYN telescope in the north and the CTIO Blanco telescope in the south. Follow-up spectroscopy was then accomplished via the Hydra multi-object spectrographs of these same two telescopes. They found between 60 and 160 tracers per galaxy, for which radial velocities were estimated. Their median measurement error was $\sim 6 \text{ km s}^{-1}$. In all cases the velocity measurement errors were $< 15 \text{ km s}^{-1}$. Herrmann & Ciardullo (2009b) find that 4 of their discs appear to have a constant M/L out to ~ 3 optical scale lengths. Beyond this radius, σ_z flattens out and remains constant with radius. Herrmann & Ciardullo (2009b) suggest that this behavior could be due to an increase in the disc mass-to-light ratio, an increase in the contribution of the thick disc, and/or heating of the thin disc by halo substructure. They also find a correlation between disc maximality and whether the galaxy is an early or late type spiral. They note that the later-type (Scd) systems appear to be clearly submaximal, with surface mass densities less than a quarter of that needed to reproduce the central rotation curves, whereas in earlier (Sc) galaxies (like NGC 628) this discrepancy is smaller, but still present; only the very early-type Sab system M94 has evidence for a maximal disc (Herrmann & Ciardullo 2009b). Fig. 1.5 shows the results for the galaxy M101 (Herrmann & Ciardullo 2009b). The fact that the vertical velocity dispersion remains constant at large radii, rather than dropping off exponentially, indicates the submaximal nature of the disc of this galaxy.

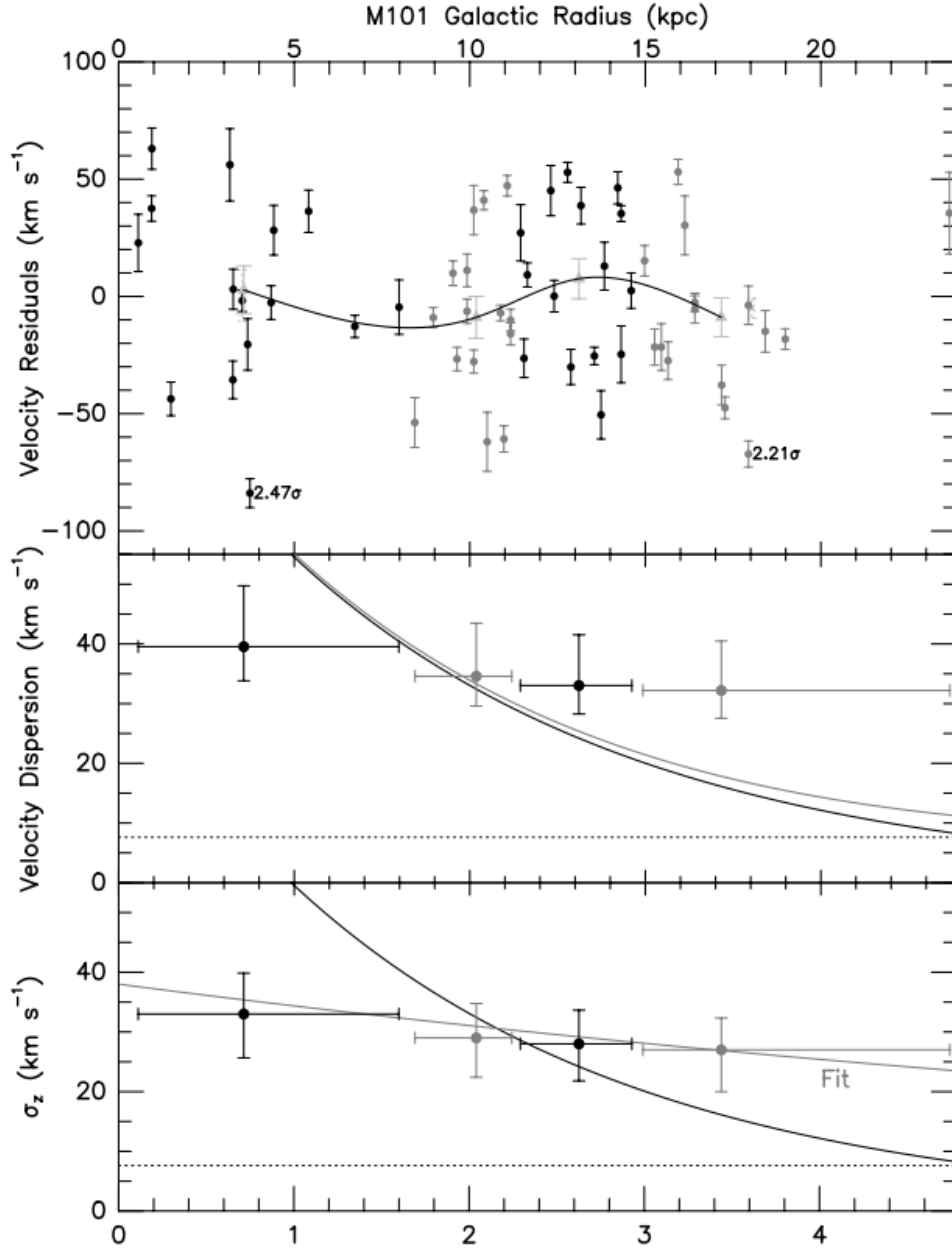


Figure 1.5: Results from Herrmann & Ciardullo (2009b) for the disc galaxy M101. Top panel shows the PNe radial velocities, middle panel shows the line-of-sight velocity dispersion, and the bottom panel shows the vertical velocity dispersion, all as a function of galactic radius. There are 15 objects in each radial bin. PNe rejected as non-disc objects are identified in the top panel; these objects are not included in the lower plots. Some HII region contaminants are plotted as light gray crosses. The light gray triangles and black curve in the top panel indicate the average residual velocity in each bin. The alternating black and dark gray points illustrate the radial bins. In the two lower panels, the dotted line shows the median velocity error, the solid black curve denotes an exponential with twice the galaxy’s I-band scale length, and the gray curve adds these two relationships in quadrature. This last curve is the one expected for a constant h_z , constant M/L disc. The gray line in the lower panel illustrates the best-fit two-component model for the galaxy, using an internal scale height of 300 pc. The profile flattens dramatically in the outer disc, indicating its submaximality.

1.2.4 The DiskMass Survey

The DiskMass Survey (DMS; Bershady et al. 2010a) used integral-field spectroscopy to measure the stellar kinematics of the discs of near face-on galaxies observed with the SparsePak and PPak instruments. The DMS selected their sample from the UGC, which included 146 nearly face-on galaxies with $H\alpha$ fields that had $B < 14.7$ and disc scale lengths between 10 and 20 arcsec. This selects galaxies with ~ 3 scale lengths within the SparsePak field of view for high surface-brightness galaxies and 2 scale lengths for lower surface-brightness galaxies. Therefore, their galaxies were relatively distant (median distance = 66 Mpc), in order to have 3 scale lengths within the field of view. They then had a subset of 46 galaxies for which they obtained stellar velocities and velocity dispersions (Bershady et al. 2010a). The survey was complemented by 4-70 μm Spitzer IRAC and MIPS photometry, ground-based UBVRIJHK photometry, and HI aperture-synthesis imaging.

The stellar kinematics of their target galaxies were measured from the Mg Ib and Ca II regions of the spectra. They also observed 150 template stars in the same instrumental configurations as the source observations for Mg Ib and Ca II regions. Although the DMS had an emphasis on giant stars for their analysis, the templates covered a large range of temperature, surface gravities and metallicities. They combine IFU fibers in azimuthal rings to measure a single σ_{LOS} at a given radius. They apply a cross-correlation technique to determine the σ_{LOS} . If G is the galaxy spectrum, T the template and B the broadening function, and $\circ$ denotes cross-correlation, $\otimes$ denotes convolution, then the DMS analysis compares the cross-correlation of a broadened and redshifted template with an unbroadened, unshifted template $((T \otimes B) \circ T)$ to the cross-correlation of the galaxy spectrum with the unbroadened, unshifted template ($XC \equiv G \circ T$). They compare, in a χ^2 sense, only the core of the correlation peaks, finding a region of 1.7 times the FWHM of the XC peak to be optimal in terms of precision (Bershady et al. 2010b).

The discs in their sample contribute typically 15% to 30% of the dynamical mass within 2.2 disc scalelengths, with percentages increasing systematically with luminosity, rotation speed, and redder color. These trends indicate that the mass ratio of disc-to-total matter remains at or below 50% at 2.2 scale length, even for the most rapidly rotating discs ($V_{max} \geq 300 \text{ km s}^{-1}$). The conclusion is that spiral discs are generally submaximal (Bershady et al. 2011). They find that at radii larger than 1.5 radial scale length, σ_{LOS} tends to decline slower than the best-fitting exponential function, which may be due to an increase in the disc M/L , disc flaring, or disc heating by the dark-matter halo (Martinsson et al. 2013b). An alternate possibility, not discussed in DMS, is that the slower decline of the dispersion may be due to the increasing contribution of the gas layer to the vertical gravitational field. We show later in our work the influence that this gas layer has on the total gravity. Herrmann & Ciardullo (2009b) had reported a similar result as we well for their sample of galaxies, using PNe as tracers. The DiskMass survey used K-band surface brightness profiles to calculate the M/L of the stellar disc. The M/L was found to be constant for all the galaxies in their sample. The mean M/L was found to be 0.31 ± 0.07 . Using these calculated values of M/L , they performed rotation-curve

decompositions. They compared these results to the traditionally used maximum disc hypothesis and found that the galaxies in their sample are submaximal, such that at 2.2 disc scale lengths the ratios between the baryonic and total rotation curves are less than 0.75 (Martinsson et al. 2013a). Fig. 1.6 shows a key plot from the results of the DiskMass survey, showing the relation between the central vertical velocity dispersion as a function of the rotation speed of the galaxy. The plot demonstrates that all the galaxies in their sample were found to be submaximal.

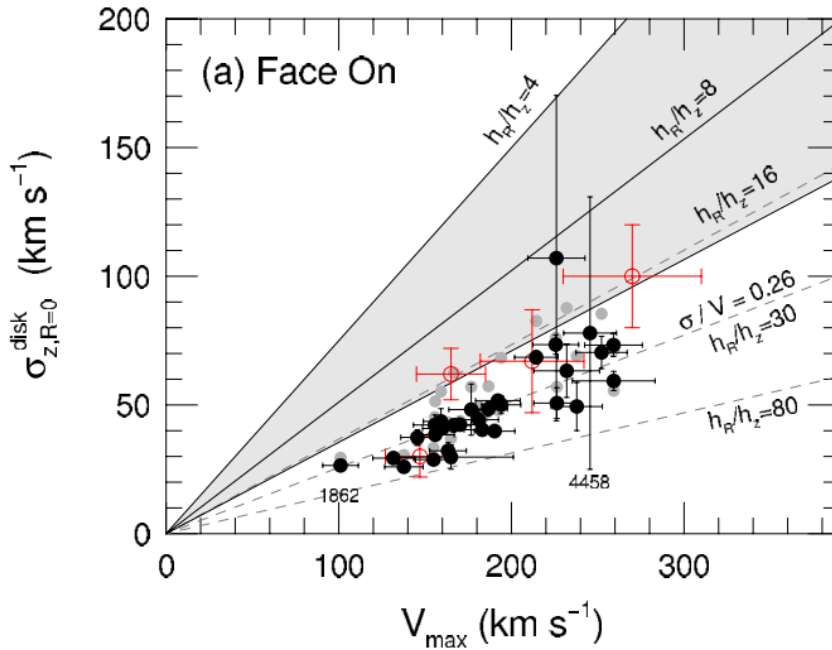


Figure 1.6: The central vertical velocity dispersion as a function of maximum gas rotation speed. The filled circles are the galaxies from the DiskMass survey and the open circles are from the work by Bottema (1993). The lines show the maximum rotational velocity allowed for self-gravitating galactic discs of different oblateness. Maximum discs in the observed oblateness range would fall in the gray shaded region.

1.2.5 Disc Modelling

All of the earlier works discussed above are observational studies, where M/L is calculated from integrated light spectra (or using PNe, in the case of Herrmann et al. 2008). Several key papers have attempted to solve the disc-halo degeneracy by modelling the galaxy into the disc and halo components. We discuss some of them briefly. Athanassoula et al. (1987) used dynamical arguments to create mass models for a sample of spiral galaxies by decomposing them into the dark halo, bulge and disc by assuming that the M/L of the bulge and disc do not vary radially. Applying constraints set by the swing amplifier theory (Toomre 1981), they find that there is only a small range of allowed M/L of the disc. All, except one, of their

galaxies seem to satisfy the maximum disc hypothesis. The exception, NGC 4736, can be explained in terms of the reshuffling of matter by the spirals (Athanasoula et al. 1987).

Debattista & Sellwood (2000) use hydrodynamical simulations to show that bars in galaxy models with haloes of moderate density and a variety of velocity distributions all have a strong drag from dynamical friction. This frictional drag decreases the bar pattern speed, shifting the corotation point out to distances well in excess of those estimated in barred galaxies. The halo angular momentum required to avoid strong braking is unrealistically large, even when rotation is confined to the inner halo only (Debattista & Sellwood 2000). They conclude that bars are able to maintain their observed high pattern speeds only if the halo has a central density low enough for the disc to provide most of the central attraction in the inner galaxy (Debattista & Sellwood 2000). They conclude that all bright high surface brightness disc galaxies have a maximal disc (also see Sellwood 1999).

1.3 Motivation

All the earlier observational studies described in the previous section have an important conceptual problem that has so far been overlooked. Equation 1.6 comes from the vertical Jeans equation for an equilibrium disc. It is therefore essential that the vertical disc scale height h_z and the vertical velocity dispersion σ_z should refer to the same population of stars. This raises a potential problem as I discuss below.

It has long been known that the velocity dispersion of stars in the Galactic thin disc near the Sun depends on their age (see e.g. Delhaye 1965 for a summary). The young disc stars with ages less than a few Gyr have $\sigma_z \sim 10 - 12 \text{ km s}^{-1}$ and stars older than $\sim 2 \text{ Gyr}$ have $\sigma_z \sim 20 \text{ km s}^{-1}$, where σ_z is the velocity dispersion in the vertical direction. Several more recent works have looked at the structure of the age-velocity relation of thin disc stars and have found similar results (Freeman 1991; Edvardsson et al. 1993; Gomez et al. 1997; Quillen & Garnett 2000): a steady increase in σ_W for stellar ages up to $\sim 2 - 3 \text{ Gyr}$ and then a roughly constant velocity dispersion for stars with ages between about $3 - 10 \text{ Gyr}$. Based on these results, if we were to look at the vertical velocity distribution of thin disc stars near the sun, we would find that the data could be well represented by two Gaussians – one with a standard deviation of $\sim 10 - 12 \text{ km s}^{-1}$ representing the younger stars and the other with a standard deviation of $\sim 20 \text{ km s}^{-1}$ representing the older stars. Fig. 1.7 shows the vertical velocity dispersion as a function of the age for stars in the solar neighbourhood (Quillen & Garnett 2000). A more recent independent version of this figure is shown later in Fig. 4.7.

In external galaxies, the dispersion σ_z is usually measured from integrated light spectra near the Mg b lines ($\sim 5150 - 5200 \text{ Å}$), since this region has many absorption lines and the sky is relatively dark. The discs of the gas-rich galaxies for which good HI rotation data are available usually have a continuing history of star formation

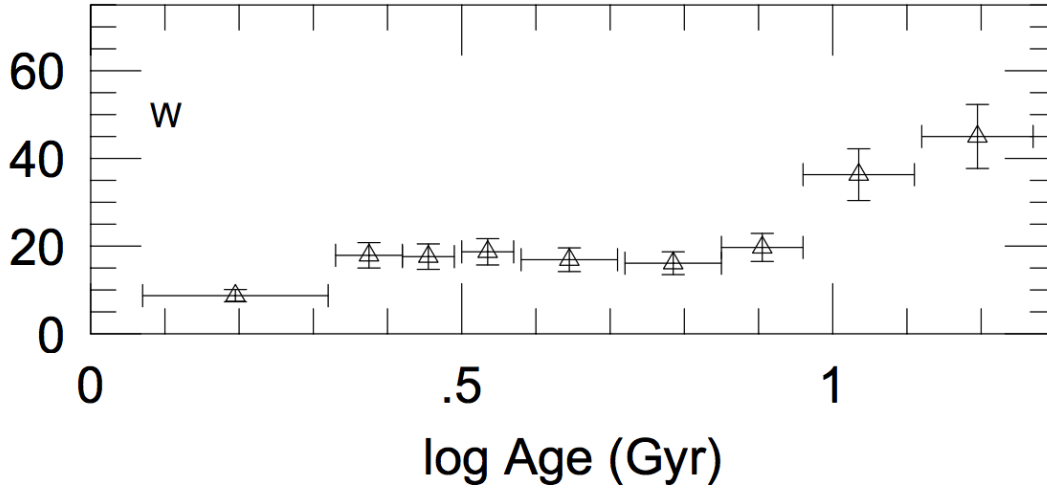


Figure 1.7: The vertical velocity dispersion of the stars in the solar neighbourhood as a function of their age (Quillen & Garnett 2000). The younger stars have an average dispersion of $\sim 10 \text{ km s}^{-1}$ and the older thin disc stars have a dispersion of $\sim 20 \text{ km s}^{-1}$. The thick disc stars have a much larger dispersion of $\sim 40 \text{ km s}^{-1}$.

and therefore include a population of young (ages $< 2 \text{ Gyr}$), kinematically cold stars among a population of older, kinematically hotter stars, similar to the age-velocity relations obtained for stars in the solar neighbourhood. The red giants of this mixed young + old population provide most of the absorption line signal that is used for deriving velocity dispersions from the integrated light spectra of galactic discs. These same giants typically contribute about half of the light of the V-band integrated light spectra of discs.

On the other hand, the scale height h_z is obtained from red and near-infrared photometry of edge-on disc galaxies. Disc galaxies have prominent dust lanes that make observations at shorter wavelengths challenging. NIR observations are dominated by the red giants of the older, kinematically hotter population with typical ages $> 2 \text{ Gyr}$ which have larger scale heights than the kinematically cold, young giants. These scale heights have been shown to correlate with other observable properties of the galaxy such as its rotational velocity and central surface brightness (see for e.g. de Grijs et al. 1997, Yoachim & Dalcanton 2006, Kregel et al. 2005). Hence, for any galaxy that we have velocity dispersion for, we can get the scale heights of the kinematically hotter stars.

In Eqn. 1.6, we should ideally be using the velocity dispersion of the older disc stars in combination with the scale heights of this same population for an accurate determination of the surface mass density. However, in practice, because of limited signal-to-noise ratios (SNR) for the integrated light spectra of the discs, previous integrated light measurements of the disc velocity dispersions usually adopt a single kinematical population for the velocity dispersion whereas, ideally, the dispersion of the older stars should be extracted from the composite observed spectrum of the younger and older stars to match the scale height for the same population.

Adopting a single kinematical population for a composite kinematical population

gives a velocity dispersion that is smaller than the velocity dispersion of the old disc giants (for which the scale height was measured), and hence underestimates the surface density of the disc. A maximal disc will then appear submaximal. This problem potentially affects the usual dynamical tracers of the disc surface density in external galaxies, like red giants and planetary nebulae, which have progenitors covering a wide range of ages. It therefore affects most of the previous studies. Flynn & Fuchs (1994) demonstrated the presence of bright, kinematically colder stars in the solar neighbourhood. They recognised the importance of isolating the old K-giants for dynamical measures of the surface density of the Galactic disc.

In this thesis, we demonstrate that it is possible to extract the vertical velocity dispersion of the hot component from high SNR data, to be used along with the scale height of the same population. We use a range of dynamical tracers – K-giants in the solar neighbourhood, stellar absorption spectra in the inner regions and PNe in the outer regions of a sample of nearby face-on discs to prove our hypothesis. We demonstrate that using the dispersion of the kinematically hot component along with the scale height will lead to these galaxies having maximal discs.

1.4 Thesis Outline

In this thesis, we will build on previous studies determining the surface mass densities of nearby spiral galaxies. The goal of this project is to resolve the conceptual problem that was overlooked in earlier surveys. Our aim is to extract two vertical velocity dispersions for our sample of star forming galaxies, one representing the younger, kinematically colder thin disc stars and the other representing the older, kinematically hotter thin disc stars. The dispersion of the hotter component, will then be used with the near-infrared scale height determined from previous studies to calculate the surface mass density of the disc. Once the surface mass density has been determined, we then use available photometric data to calculate the M/L for the discs of these galaxies. These M/L are then used with available HI rotation curves to decompose them into contributions from the disc and the dark halo.

Chapter 2 looks at a sample of K-giants in the solar neighbourhood. We look at the data available from our own galaxy to test our hypothesis on whether the thin disc is, in fact, made of two Gaussian components representing the young and old stars. We find the vertical velocity distribution best fit by two components with dispersions of $9.6 \pm 0.5 \text{ km s}^{-1}$ and $18.6 \pm 1.0 \text{ km s}^{-1}$, which we interpret as the dispersions of the young and old disc populations respectively. Combining the (single) measured velocity dispersion of the total young + old disc population ($13.0 \pm 0.1 \text{ km s}^{-1}$) with the scale height estimated for the older population would underestimate the disc surface density by a factor of ~ 2 . Such a disc would have a peak rotational velocity that is only 70% of that for the maximal disc, thus making it appear submaximal. In the near future, this work can be put on a firmer footing as better age-velocity data becomes available from (say) the Gaia survey, asteroseismology data, and other large spectroscopic surveys.

Chapter 3 describes in detail the instruments that we used to survey our sample of

nearly face-on disc galaxies. We use absorption line spectroscopy in the inner regions of these galaxies (similar to the DiskMass survey) using the VIRUS-W instrument on the 2.7 m telescope at McDonald observatory in Texas. We also complement our absorption line studies, using PNe as dynamical tracers in the outer regions of these galaxies (similar to the work by Herrmann et al. 2008). We use the Planetary Nebulae Spectrograph (PN.S) on the 4.2 m William Herschel Telescope at La Palma. The technical details such as the instrument capabilities, observations carried out and the reduction process are described in this chapter.

Chapter 4 describes our analysis on the face-on galaxy NGC 628. This is the most face-on galaxy in our sample, which proved advantageous in extracting the vertical velocity dispersions from the in-plane components. We had IFU data within the inner ~ 1 scale length and PN.S data out to ~ 4 scale lengths. This is one of the galaxies that were studied by Herrmann et al. (2008). We compare our results from those obtained by Herrmann & Ciardullo (2009b) for the PNe analysis and look at the difference in the surface mass density by considering one component and two components in the vertical velocity dispersion extraction.

Chapter 5 and 6 describe the results of our analysis for the galaxies NGC 6946 and NGC 5457 respectively. We, again, present the analysis of the IFU study in the inner regions and PNe study in the outer regions of these galaxies. These galaxies are more inclined than NGC 628, which presents new challenges.

In Chapter 7 we present our conclusions and future work from this thesis. We demonstrate the importance of extracting out the dispersion of the hotter component to be used with the scale height of this same population of tracers. Neglecting to extract this component can lead to erroneously concluding that galaxy discs are submaximal. An important follow up work would be to extend a similar analysis to higher redshift galaxies to study the onset of the thin disc in spiral galaxies. It is known that, in the Milky Way, the thin disc formation did not begin until about 9 Gyr ago, corresponding to $z = 1.5$ (e.g. Bensby et al. 2014). The thin disc is the dominant stellar component in later-type spiral galaxies, and it would be very interesting to know when the thin disc begins to form in spirals other than the Milky Way. I propose to undertake integrated light spectroscopy of near-face-on galaxies in the redshift range from about 0.8 to 1.3, at a rest wavelength of about 5200 Å. The goal is to determine the redshift of onset of thin disc formation. The methods we developed for this work can be applied to galaxies at $z < 1.3$ to disentangle the thin and thick disc in these galaxies. This project will considerably advance our understanding of galaxy assembly by observationally answering the question: at what redshift did the thin disc start to assemble?

K GIANTS IN THE SOLAR NEIGHBOURHOOD

2.1 Introduction

The Milky Way is a typical disc galaxy. The young and old stellar thin disc populations that we expect to find in external spiral galaxies (as discussed in Chapter 1), should in principle be found in our galaxy as well. These young and old stellar components have very different vertical velocity dispersions and scale heights, which will affect the way that surface mass densities, and hence mass-to-light ratios (M/L) are calculated. In this chapter, we use a sample of K-giants in the solar neighbourhood to check our hypothesis that there really are two thin disc components among the red giants – a younger, kinematically colder population of stars and an older, kinematically hotter population of stars and their effect on surface mass density calculations. Flynn & Fuchs (1994) was one of the earliest works to demonstrate the presence of bright, kinematically colder stars in the solar neighbourhood. They recognised the importance of isolating the old K-giants for dynamical measures of the surface density of the Galactic disc.

Fig. 2.1 presents a synthetic colour magnitude diagram computed using IAC-Star (see Aparicio & Gallart 2004) with the Teramo stellar evolution library and the Castelli & Kurucz bolometric correction library, to show the location of these younger and older red giants. The adopted star formation history has the exponential form $\exp(-t/\beta)$ with $\beta = 20$ Gyr. We used a Kroupa IMF and a linear chemical enrichment law, with a mean metallicity $Z = 0.006$ and 0.019 at $t = 0$ Gyr and $t = 13$ Gyr respectively. We introduced a spread of ± 0.4 dex in the metallicities at all ages, to match the dispersion in the observed age-metallicity law in the solar neighbourhood (e.g. Haywood 2008). Stars younger than 2 Gyr are shown in red in Fig. 2.1 and the black points are for older stars. Fig. 2.1 shows that the younger giants are more likely to be among the most luminous stars on the giant branch (see Appendix A for the fraction of total light contributed by the giants). We also show the $M_K, J - K$ colour-magnitude diagram for the same simulation, to indicate the contribution that the older giants make to the near-IR surface brightness in photometric studies of edge-on discs.

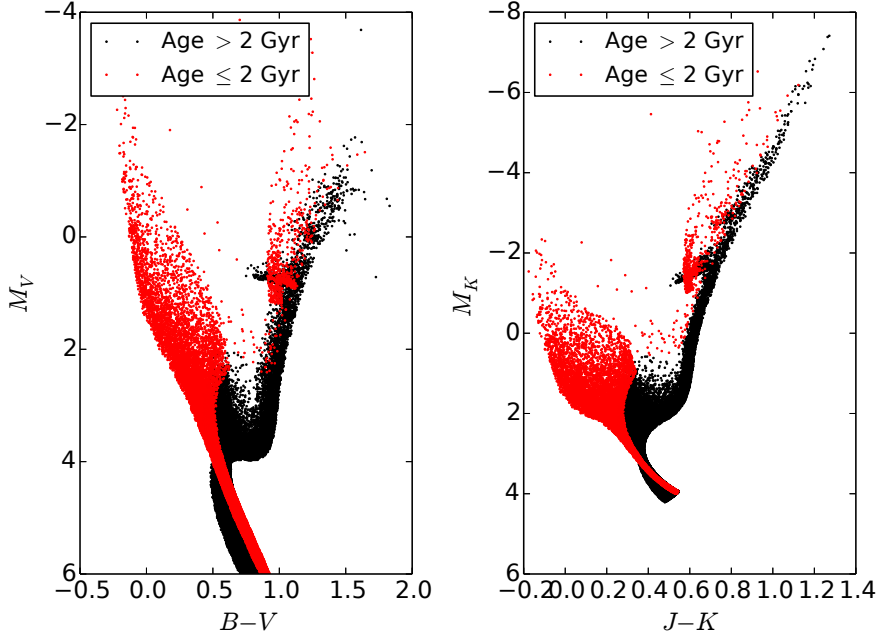


Figure 2.1: The CMD computed from IAC-STAR for a disc with an exponentially declining star formation law. The red points are stars with ages ≤ 2 Gyr. The left panel shows the CMD in the V-band. The right panel shows the CMD in the near-infrared. The old giants are the brightest stars in IR.

2.1.1 The surface density of the Galactic disc near the sun

As discussed in Chapter 1, integrated light spectroscopy and estimates of the disc scale height can be used to measure the surface density of the discs of external galaxies. In the Milky Way, the velocities and spatial distributions of individual tracer stars near the sun can be used for the same purpose. We briefly review the results from earlier works in Table 2.1, because they provide a useful context for the integrated light observations of external galaxies.

Author	Σ_{disc}	$\Sigma_{total}(1.1 \text{ kpc})$	Sample
Kuijken & Gilmore (1989c,a,b)	$48 \pm 8 \text{ M}_{\odot} \text{ pc}^{-2}$	$71 \pm 6 \text{ M}_{\odot} \text{ pc}^{-2}$	K-dwarfs
Flynn & Fuchs (1994)	$52 \pm 13 \text{ M}_{\odot} \text{ pc}^{-2}$		K-giants
Holmberg & Flynn (2004)	$56 \pm 6 \text{ M}_{\odot} \text{ pc}^{-2}$	$74 \pm 6 \text{ M}_{\odot} \text{ pc}^{-2}$	K-giants
Bovy & Rix (2013)	$38 \pm 4 \text{ M}_{\odot} \text{ pc}^{-2}$	$68 \pm 4 \text{ M}_{\odot} \text{ pc}^{-2}$	G-dwarfs

Table 2.1: Studies that have looked at the solar neighbourhood to estimate the surface density of the Galactic disc and the total surface density (disc + dark halo).

The values obtained from these different studies agree well. The implications regarding the maximality of the Milky Way’s disc are uncertain, because the radial scale length of the Galactic disc is not accurately known.

2.1.2 Are Discs really so Submaximal?

In the following sections, we analyse the K-giants in the solar neighbourhood, to demonstrate the existence of different populations of stars with different vertical velocity dispersions and discuss the implications for the decomposition of the HI rotation curves of external galaxies. While the K-giants dominate the velocity dispersion signal in the integrated spectra of external discs, it is only near the Sun that we can examine in detail the composite kinematical makeup of the K-giant population, and work out the implications for integrated light spectroscopy of an external disc that has a similar star formation history to the Galactic disc near the Sun. In particular, we would like to evaluate the significance of a cold core of K-giants among the kinematically hotter stars of the old disc.

Section 2.2 describes our data sample and section 2.3 describes the analysis. The results are discussed in section 2.4. Section 2.5 uses the Besançon model as a check on any unanticipated selection effects that our sample of giants may have, section 2.6 uses the Besançon model to look at the implications for external galaxies, section 2.7 has our conclusions and section 2.8 discusses our future plans for this project.

2.2 Selection of Sample

We would like to construct a sample of nearby red giants that has age and kinematics for each star. Currently, these data are not yet available but are soon expected from asteroseismology of red giants (e.g. Soderblom 2010). At present, guided by Fig. 2.1, we can use giants of known vertical velocity (W velocity) and absolute magnitude to look at their distribution over kinematics and luminosity. We use two different samples to build up our data set – a sample of K giants in the South Galactic Pole (SGP), for which the W velocities come mainly from the radial velocities, and giants from the Bright Star Catalog.

The Flynn & Freeman (1993) sample (hereafter FF) is a sample of 560 K-giants at the SGP with $V < 11.0$. It was selected from the following sources:

- Henry Draper (HD) stars with spectral types between G8 and K5, brighter than luminosity class V, from the Michigan Catalog Volumes III and IV (Houk 1982; Houk & Smith-Moore 1988),
- The Eriksson (1978/1995) sample of SGP stars with $0.95 < B - V < 1.55$ and $V < 11.0$,
- A sample of fainter giants from the Zeiss 6-inch camera on the Oddie telescope at Mount Stromlo Observatory (see FF).

We used a subset of 303 stars from the FF sample with measured $B - V$, radial velocity and absolute magnitude (M_V). The absolute magnitudes in the FF sample were originally estimated using the intermediate-band photometric David Dunlop Observatory (DDO) system. Holmberg & Flynn (2004) later compared the DDO absolute magnitudes with the more accurate Hipparcos absolute magnitudes and

found some systematic offsets in the DDO system. The absolute magnitudes of our stars from the FF sample were re-calibrated as suggested by Holmberg & Flynn (2004). The expected absolute magnitude of the red giant branch clump stars ($M_V \sim 0.8$) is consistent with the revised magnitude scale.

The sample of 303 FF red giant stars with colour, magnitude and radial velocity information is not large enough to evaluate the detailed structure of the W velocity distribution function, so we increased our sample size by adding giants from the Bright Star Catalog (BSC) (Hoffleit & Jaschek 1991). The BSC is more or less complete to $V = 7$. We chose stars from the BSC that have the same spectral type as the FF stars, i.e from G8III to K5III.

2.3 Analysis

In this section, we calculate the space velocities for our sample of stars and represent the distribution of W velocity in terms of different populations of stars.

2.3.1 Vertical Velocities of the Sample of Giants

Of the above subset of 303 stars from the FF sample, proper motions for 300 are available from the UCAC4 catalogue (Zacharias et al. 2013); 134 of them have parallaxes and associated errors from the extended Hipparcos catalogue (Anderson & Francis 2012). Photometric distances for all 300 stars were calculated using the data in FF and the corrected M_V values using the method described by Holmberg & Flynn (2004). The M_V values have errors of 0.35 mag (Holmberg & Flynn 2004) and the apparent V magnitudes in Flynn & Freeman (1993) have typical errors ~ 0.02 mag. Therefore, our photometric distances typically have a 16% error. For the final calculation of W velocities, we compared the relative errors of the data from the Hipparcos catalog (where available) and the photometric distances, and used the distance with the smaller relative error.

The BSC catalog has radial velocities with typical errors $< 1 \text{ km s}^{-1}$. It also contains the parallaxes and proper motion from the Hipparcos catalog. Our final sample now contains 1740 stars.

The stellar W velocities were calculated as described in Johnson & Soderblom (1987), with the W velocity positive towards the North Galactic Pole. The errors of the W velocities were again calculated as in Johnson & Soderblom (1987). For our study of the W velocity distribution function, only stars with W velocity errors $< 5 \text{ km s}^{-1}$ were retained in the sample to avoid contamination of the velocity distribution by measurement errors. Large errors will compromise our attempt to recover the young component that has small dispersions. Our sample now contains W velocities for 1567 stars. Fig. 2.2 shows their W velocities against the absolute magnitude, M_V . The W velocities are heliocentric, and the solar motion (our data has mean $W = -7 \text{ km s}^{-1}$) is evident in Fig. 2.2. The rapid decrease in the stellar density for stars with $M_V > 1$ results from the apparent magnitude and spectral type limits of our sample. The smaller velocity dispersion of the younger disc giants (M_V

< 0) is also evident. The older stars show a visibly larger spread in W velocities. Fig. 2.3 shows the σ_W vs. M_V for our sample. The low dispersion of the colder component at $M_V < -2$ is clearly visible. Flynn & Fuchs (1994) also show the presence of this cold, bright population of stars in the solar neighbourhood.

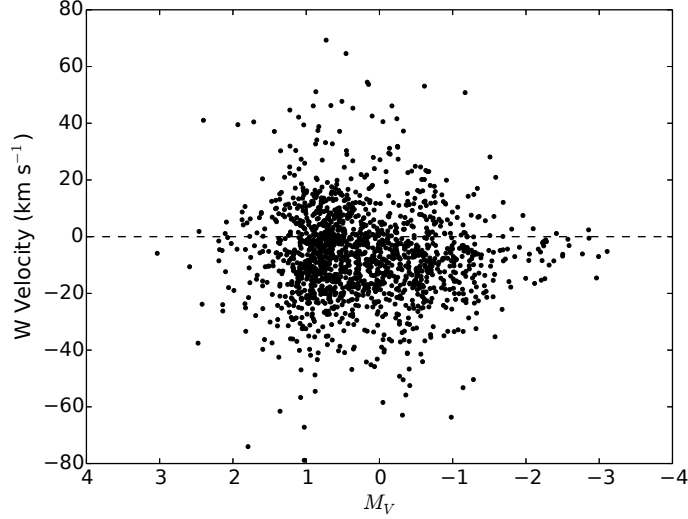


Figure 2.2: W velocities versus absolute magnitude for the nearby giants. The colder stars with smaller dispersions can be seen at $M_V \leq -2$. The offset from zero of the mean W -velocity is due to the 7 km s^{-1} reflex W -motion of the sun.

2.3.2 Age-Velocity Relation

It has long been known that the velocity dispersion of stars in the Galactic thin disc near the Sun depends on their age (see e.g. Delhaye 1965 for a summary). The young disc stars with ages $< 2 \text{ Gyr}$ have $\sigma_W \sim 10 - 12 \text{ km s}^{-1}$ and stars older than $\sim 2 \text{ Gyr}$ have $\sigma_W \sim 20 \text{ km s}^{-1}$. Several more recent works have looked at the structure of the age-velocity relation of thin disc stars and have found similar results (Freeman 1991; Edvardsson et al. 1993; Gomez et al. 1997; Quillen & Garnett 2000): a steady increase in σ_W for stellar ages up to $\sim 2 - 3 \text{ Gyr}$ and then a roughly constant velocity dispersion for stars with ages between about $3 - 10 \text{ Gyr}$. Based on these results, if we were to look at the W velocity distribution of thin disc stars near the sun, we would find that the data could be well represented by two Gaussians – one with a standard deviation of $\sim 10 - 12 \text{ km s}^{-1}$ representing the younger stars and the other with a standard deviation of $\sim 20 \text{ km s}^{-1}$ representing the older stars.

Other studies (e.g. Wielen 1977) indicate that the velocity dispersion of the thin disc stars does not plateau for the older stars but continues to increase steadily with age. In their study of the Geneva-Copenhagen sample, Casagrande et al. (2011) find that the velocity dispersion continues to increase up to an age of $\sim 10 \text{ Gyr}$. Their derived rate of increase for the dispersion of the older stars depends on the adopted stellar models and the abundance and age cuts imposed on the sample (see their Fig.

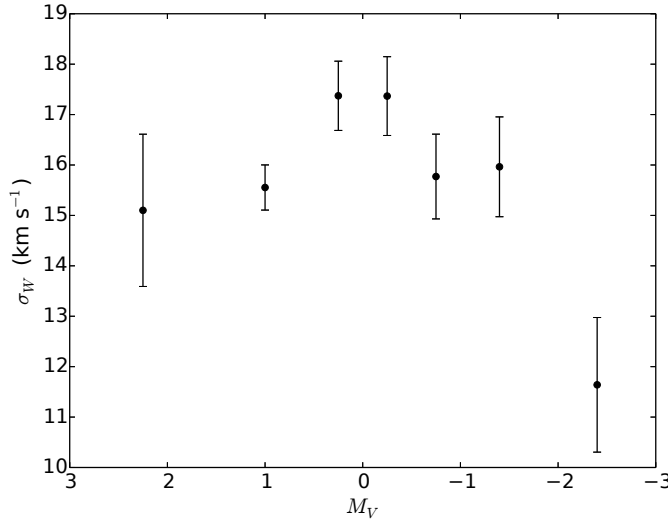


Figure 2.3: The vertical velocity dispersion (σ_W) versus absolute magnitude for the nearby giants. The brighter stars ($M_V < -2$) are much colder as indicated by their low σ_W value.

17). However, we note that if the thick disc stars are excluded, then the age-velocity relation from Casagrande et al. (2011) for the thin disc shows a constant velocity dispersion for the older stars, not the rising dispersion that was shown in their original paper (see our Fig. 4.7 in Chapter 4). If this continuously rising velocity dispersion with age represents the W velocity distribution of the nearby thin disc, then a simple two-component distribution would not be a good representation of the velocity distribution. A more complex model would be required. For the purpose of this thesis, we will adopt the former model, assuming that two approximately Gaussian velocity components (older and younger) are present among the giants of the thin disc.

2.3.3 Multiple Populations of Stars

Our aim is to determine whether the kinematical parameters for two different population of stars (i.e the younger, colder population and the older, hotter component) can be extracted from our sample of W velocities of nearby stars. In order to do this, we constructed a generalized histogram of W velocities by representing the velocity of each star as a Gaussian of unit area with mean at its observed W velocity and the error in W velocity as its standard deviation (see Fig. 2.4). The motivation for using a generalized histogram was to avoid the effects of binning. Our Gaussian models are of the form:

$$\sum_{k=1}^n A_k e^{-(x-\mu_k)^2/2\sigma_k^2} \quad (2.1)$$

where A is the amplitude, μ is the mean and σ is the standard deviation of the

Gaussian. For a single Gaussian model, $n = 1$ and for a double Gaussian model, $n = 2$.

We used the `curve_fit` module in the python `scipy.optimize` package to determine the parameters for the two Gaussians. Curve-fit uses non-linear least squares and the Levenberg-Marquardt algorithm. It requires an initial guess of parameters and returns the best-fit values, along with the covariance matrix. The errors associated with each parameter are the square roots of the corresponding elements on the diagonal of the covariance matrix. To fit a two-Gaussian model, we need to estimate 6 parameters i.e the amplitude, mean and standard deviation for each component. We will also be fitting single Gaussian models (3 parameters) for comparison.

In order to evaluate whether a two-component model is preferred over a one-component model, we compute the Akaike Information Criterion (*AIC*) which can be used to determine whether adding additional parameters results in a better fit. The *AIC* is defined by

$$AIC = n \ln(SSE) - n \ln(n) + 2p \quad (2.2)$$

where n is the number of samples, p is the number of parameters in the model, and *SSE* is the sum of the squared errors

$$SSE = \sum (y_{data} - y_{model})^2. \quad (2.3)$$

The *AIC* penalizes additional parameters in the model; the model with the lowest *AIC* is preferred.

2.4 The Two Velocity Components

We now derive the double Gaussian and single Gaussian fits to the distribution of *W* velocities for our sample of K-giants. A significant cold component is visible in the double Gaussian fit. We show again that the brightest giants ($M_V \leq -1.8$) are kinematically very cold, while the fainter giants are an almost homogenous mixture of the hot and cold populations.

Fig. 2.4 shows the generalized velocity histogram of our sample of stars (black), fit with a two component model (red). It demonstrates the presence of a colder population of stars among a hotter disc population.

The results of our single Gaussian fit and double Gaussian fit are tabulated in Table 2.2.

Using Eqn. 2.2, we get an *AIC* = 55.2 for the 2 component model and *AIC* = 155.7 for the 1-component model. Clearly, the 2-component model is preferred in this case. Fig. 2.4 shows the fit to the generalized histogram using two-component and one-component fits. The 2-component fit is visibly better than a single Gaussian fit.

The goal is to use the measured velocity dispersion and the scale height to calculate the surface density of galactic discs that are viewed more or less face-on. The adopted velocity dispersion and the calculated surface density depend on the kine-

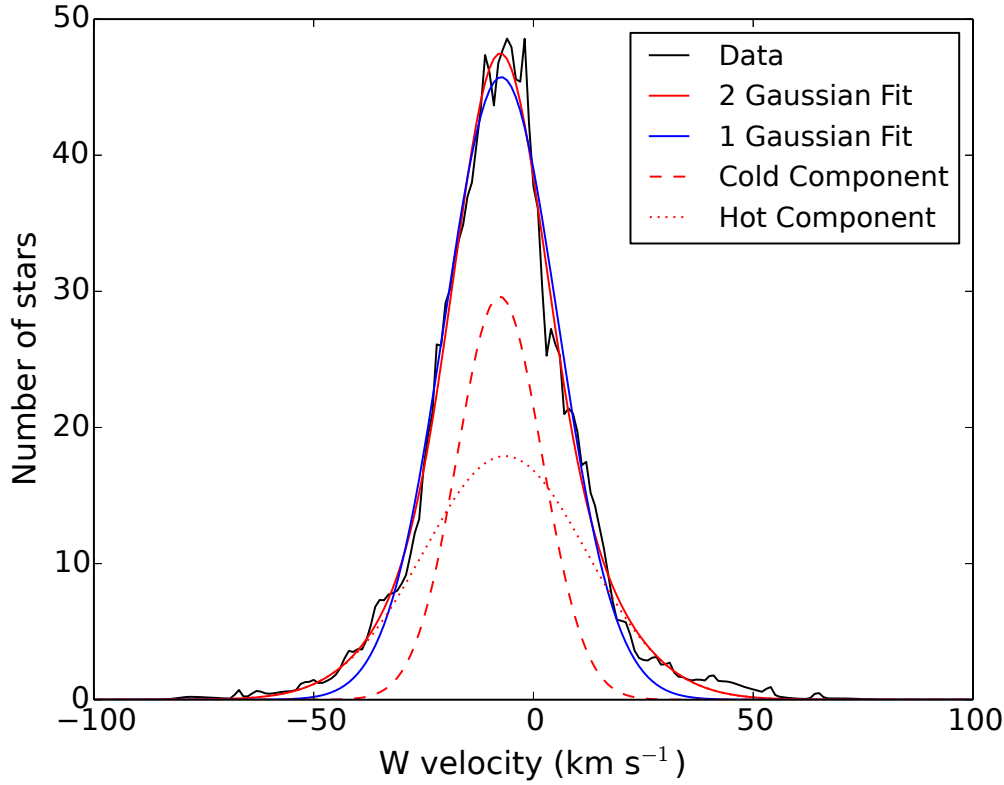


Figure 2.4: Generalised histogram of W velocities for the combined red giants from Flynn & Freeman (1993) and BSC (in black). The red curve is the best fit to the data, using 2 Gaussians to represent the colder (red dashed line) and hotter (red dotted line) components of the thin disc. The blue curve represents the best single-Gaussian fit, for comparison.

mathematical model (one component or two), and we now estimate how much difference this can make. We use Eqn. 1.1 which relates the surface density Σ , the scale height h and the velocity dispersion σ of the disc. The scale height cannot be measured directly: it is estimated from the scaling laws for the scale height, and pertains to the old disc population, as explained in section 1.3. The underlying dynamical assumption is that the disc is in vertical equilibrium in its own gravitational potential, so the scale height and the velocity dispersion should be for the same population. What is the effect on the surface density of using a single-component kinematical model to represent the disc, when in reality there are two kinematical components? The true velocity dispersion of the old disc is then the dispersion σ_{hot} of the hotter of the two components, and the true surface density of the disc is $\Sigma_{\text{true}} = f\sigma_{\text{hot}}^2/Gh$. On the other hand, if we were to use a single component kinematical model, we would calculate its surface density as $\Sigma_{\text{single}} = f\sigma_{\text{single}}^2/Gh$. The velocity dispersion σ_{single} for the single-component model is lower than σ_{hot} , as in Table 2.2 (13.0 km s⁻¹ and 18.6 km s⁻¹ respectively). The adopted scale height h is not affected by the kinematical measurements, so the effect of using the one-component model is to

	Cold Component	Hot Component	Single Gaussian Fit
Amplitude	29.6 ± 3.1	17.9 ± 3.2	45.7 ± 0.4
Mean (km s^{-1})	-7.7 ± 0.2	-6.5 ± 0.5	-7.3 ± 0.1
Sigma (km s^{-1})	9.6 ± 0.5	18.6 ± 1.0	13.0 ± 0.1
AIC		55.2	155.7

Table 2.2: The fit results for the 1 component and 2 component models. The amplitudes are in arbitrary units, as defined in Eqn. 2.1. The lower value of the AIC indicates that the two Gaussian model is preferred, despite the larger number of parameters.

underestimate the surface density of the disc.

Taking, in each case, the same scale height h for the old thin disc, the ratio of surface densities derived from using the dispersion for (a) the hotter component of a double Gaussian fit and (b) a single Gaussian fit, is

$$\frac{\Sigma_2}{\Sigma_1} = \frac{\sigma_2^2}{\sigma_1^2} = \frac{(18.6 \pm 1.0)^2}{(13.0 \pm 0.1)^2} = 2.05 \pm 0.16 \quad (2.4)$$

The subscript 1 refers to the case where we fit a single Gaussian and subscript 2 refers to the hotter (older) component of the double Gaussian fit. If we were using integrated light spectroscopy to measure the surface density of the disc of an external galaxy, in which the star formation history over the last 10 Gyr has been similar to that in the solar neighbourhood, and if we had used a single-component Gaussian velocity distribution instead of deriving the velocity dispersion of the old disc from a two-component velocity distribution, then we would underestimate the surface density of the disc by about a factor 2.

We can use Eqn. 1.1 and the dispersion for the hotter component of the two-component model in Table 2.2, to estimate the surface density of the disc near the sun and compare with the more detailed estimates of surface density given in Table 1. We assume that the old disc is vertically exponential, with a scale height $h = 300 \pm 50$ pc (e.g. Gilmore & Reid 1983) and a velocity dispersion of $\sigma = 18.6 \pm 1.0 \text{ km s}^{-1}$ as given in Table 2.2. The surface density $\Sigma = (2/3\pi) \sigma^2 / Gh = 57 \pm 12 \text{ M}_\odot \text{ pc}^{-2}$, in fair agreement with the range of estimates given for the surface density of the disc in Table 2.1¹.

In this section, we have shown that the W velocity distribution of the nearby K-giants is well represented by a two-component distribution. Fig. 2.3 shows that the more luminous giants have a smaller W velocity dispersion than the fainter giants, and we associate the two components with the older and younger stars of the thin disc.

We can visualise and quantify this effect further, by splitting the sample of stars into 3 absolute magnitude intervals: $M_V \leq -1.8$, $-1.8 < M_V \leq 0$ and $M_V > 0$. Within each group, the stars are ordered by increasing absolute magnitude. We

¹We will revisit this surface mass density in Appendix C at the end of this thesis, where we consider the influence of the cold component and gas to the total surface mass density of the disc.

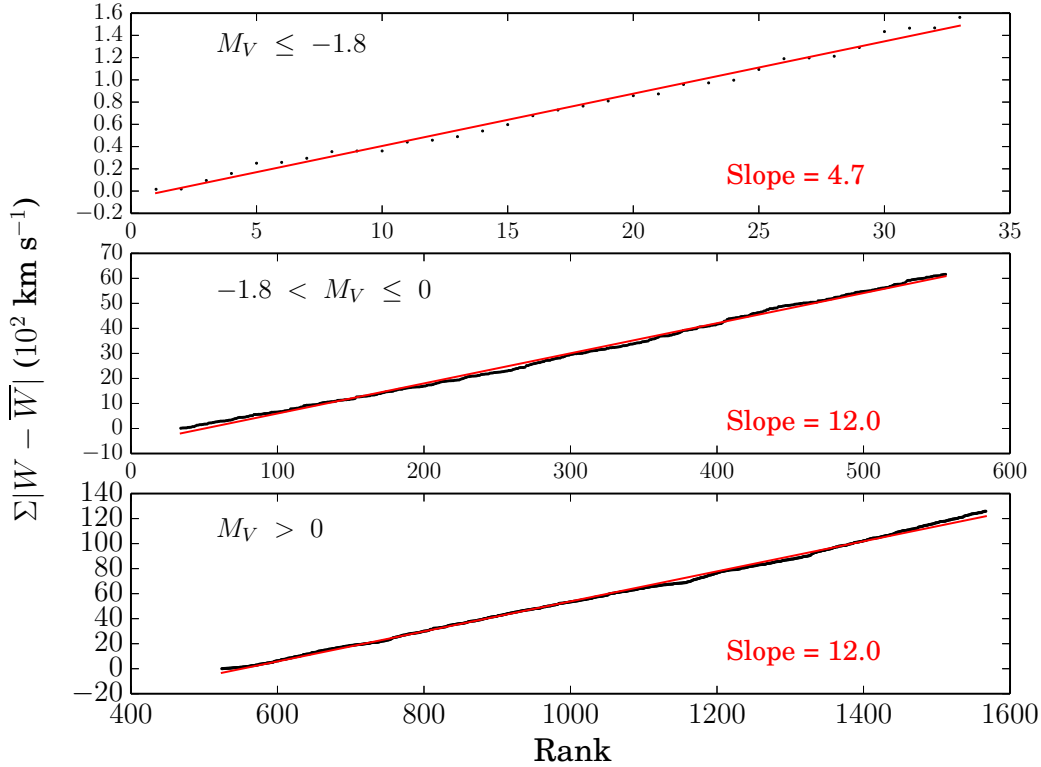


Figure 2.5: The cumulative sum of $|W - \bar{W}|$ against rank by absolute magnitude in three magnitude intervals for our giants. The x-axis shows the rank of the stars and the y-axis is the cumulative sum of W velocities. See section 2.4 in the text for further details. The upper panel is for the bright, young, kinematically colder population. The stars in the two bottom panels contain a mixed population of young and old stars. The velocity dispersion of the population is proportional to the slope of the line.

then form the cumulative sum of $|W - \bar{W}|$ vs the rank of the star, where $\bar{W}$ is the mean value of W for the group. The point of doing this kind of analysis is that, for a group of stars with homogeneous velocity dispersion (not necessarily a single Gaussian component), the plots of the sum of $|W - \bar{W}|$ against rank will be a straight line, and the slope is a measure of the velocity dispersion. Fig. 2.5 shows the outcome for each of the three absolute magnitude groups.

The red line in each panel of Fig. 2.5 is a linear fit to the data. The slope of the line $= \sqrt{2/\pi}\sigma$, where σ is the velocity dispersion. Fitting the slope of the line is equivalent to deriving a single dispersion for the velocity distribution of the stars, after setting their mean velocity to zero. The bright giants with $M_V \leq -1.8$ represent mainly the younger and kinematically colder population. Their dispersion is $\sigma = 5.9 \text{ km s}^{-1}$ which is colder than the value we obtained for the young, cold component in our two-component Gaussian decomposition.

The two panels of fainter stars with $M_V > -1.8$ are mixed populations of stars of

all ages, with similar (larger) dispersions. While the brighter stars in the top panel are clearly from a colder population, we conclude from Fig. 2.5 that the mixtures of hot and cold populations in the two lower panels are fairly similar and do not change much with absolute magnitude, because the two panels are well fit by straight lines and have similar slopes with dispersions of 15 km s^{-1} .

2.5 Comparison with Kinematics of the Besançon Model

As a check on what we have learned about the velocity distribution of the nearby thin disc from our sample of nearby giants, we did a similar study on a sample of simulated giants from the on-line Besançon model (Robin et al. 2003). This model was designed to represent the main Galactic structural components and stellar populations. It includes recipes for galactic reddening, the star formation history and the dynamical evolution which manifests as the stellar age-velocity dispersion relation (Robin et al. 2003, Table 4). Our main goal in using the Besançon model here is as a check on any significant unanticipated selection effects in our sample of giants.

Two separate simulated catalogs were generated – one to represent the FF stars and another for the BSC stars. The simulation that mimics the FF giant sample was made by choosing all stars within a distance of 1.5 kpc, $-3 \leq M_V \leq +3$, $-90^\circ \leq b \leq -75^\circ$, $V \leq 11$ and $1.0 \leq B - V \leq 1.5$. This gave ~ 3000 stars. For the BSC giant simulation, we chose stars within a distance of 0.6 kpc, $-3 \leq M_V \leq +3$, $V \leq 7$ and $0.8 \leq B - V \leq 1.8$. No cuts were made in position on the sky. This gave $\sim 10,000$ stars. Fig. 2.6 compares the luminosity functions of our sample of stars (FF and BSC: upper panel) with the luminosity function of the simulation. The red clump stars ($M_V \sim 0.8$) stand out very clearly in the Besançon model simulation as well as in our sample, as expected. All figures involving the Besançon model in the main body of the paper are using this combined simulated catalog of the FF and BSC red giants.

Fig. 2.7 shows the W velocity vs absolute magnitude for the Besançon sample of stars. As in Fig. 2.2, a kinematically colder component of bright giants can be clearly seen at $M_V < -2$. A small number of high velocity thick disc stars are present for $M_V > -2$. Fig. 2.8 is similar to Fig. 2.3 but for the Besançon sample of stars.

Fig. 2.9 is similar to Fig. 2.5 but for the Besançon simulation. As before, the brightest stars correspond to the kinematically cold component. The slope of the linear fit corresponds to a velocity dispersion $\sigma = 7.9 \text{ km s}^{-1}$ for the stars with $M_V \leq -1.8$. The two panels of stars with $M_V > -1.8$ contain stars of all ages and have again similar larger dispersions.

We made a similar analysis to that shown in Fig. 2.4, using the W velocities from the Besançon simulations to create a generalized histogram of velocities, and adopting a velocity error of 2 km s^{-1} for each star. The results are tabulated in Table 2.3.

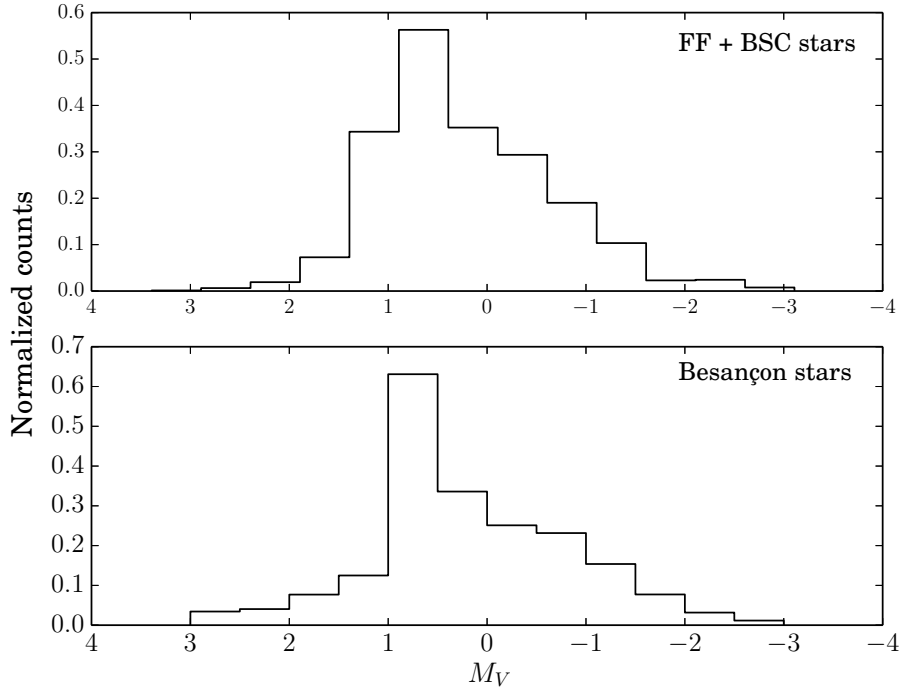


Figure 2.6: Comparison of the luminosity functions of our sample of stars with a simulation of these stars from the Besançon model. There seems to be a larger fraction of stars with $M_V \sim 1$ in our sample, but otherwise the two samples are a good match.

Fig. 2.10 shows the velocity distribution for the Besançon simulation fit with a double Gaussian model and with a single Gaussian model. Clearly, the double Gaussian is a better fit to the data.

The Besançon simulation is a good match to the kinematics of our sample of nearby giants. The two-component dispersion values are very similar to the values obtained for the FF + BSC stars. The relative numbers of stars in the two components can be calculated from the ratio of the product of the amplitude and dispersion $A\sigma$ for the two components (see Eqn. 2.1): the ratio of hot:cold stars is about 1.2:1 in both the FF + BSC sample and in the Besançon simulation.

In evaluating the contribution of the kinematically cold component to the integrated light spectrum of a disc with a star formation history like that of the solar neighbourhood, it would be useful to know the ratio of the relative contributions of the colder and hotter components to the surface brightness of the disc. This would allow us to evaluate how much each component contributes to the integrated light of the disc. To estimate this ratio, we built up another velocity histogram using the Besançon model, but this time each star was represented as a Gaussian with area proportional to its luminosity. This histogram, shown in Fig. 2.11, is then a luminosity-weighted velocity distribution. The luminosity of each star was calculated from its M_V value in the Besançon simulation of the FF and BSC catalogs

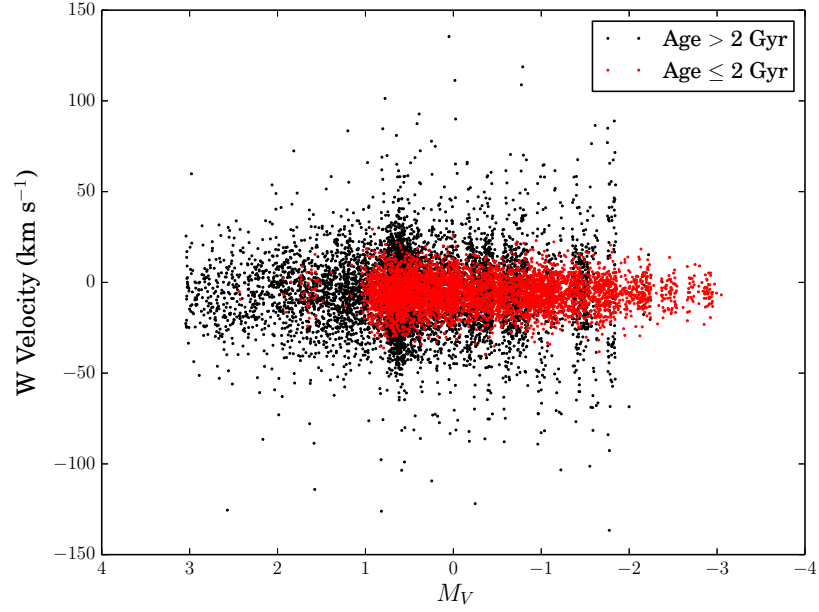


Figure 2.7: Besançon stars. Stars with $M_V \leq -2$ is comprised purely of the young population. A mixed population of young and old stars can be at $-2 < M_V \leq -1$.

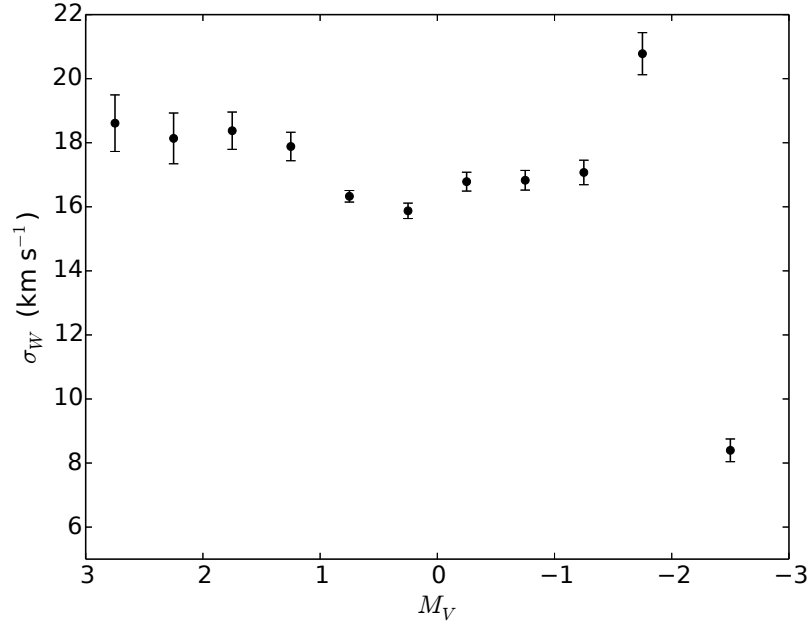


Figure 2.8: The vertical velocity dispersion (σ_W) versus absolute magnitude for the Besançon sample. The brighter stars ($M_V < -2$) are much colder as indicated by their low σ_W value.

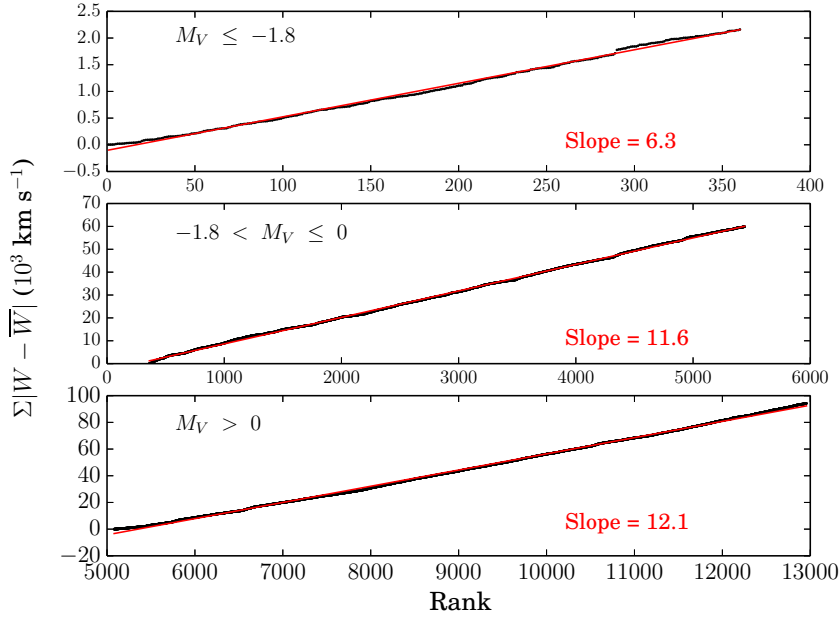


Figure 2.9: The cumulative W velocities in different magnitude ranges of the Besançon simulation. The x axis shows the rank of the stars and the y axis is the sum of modulus of $W - \bar{W}$ velocities. See text for further details.

	Cold Component	Hot Component	Single Gaussian Fit
Amplitude	264.3 ± 3.8	148.0 ± 4.0	394.4 ± 1.5
Mean (km s^{-1})	-5.64 ± 0.03	-6.26 ± 0.08	-5.82 ± 0.05
Sigma (km s^{-1})	8.95 ± 0.07	18.45 ± 0.17	13.0 ± 0.1

Table 2.3: The fit results for the 1 component and 2 component models for the Besançon sample of stars. The amplitudes are in arbitrary units, as defined in Eqn. 2.1.

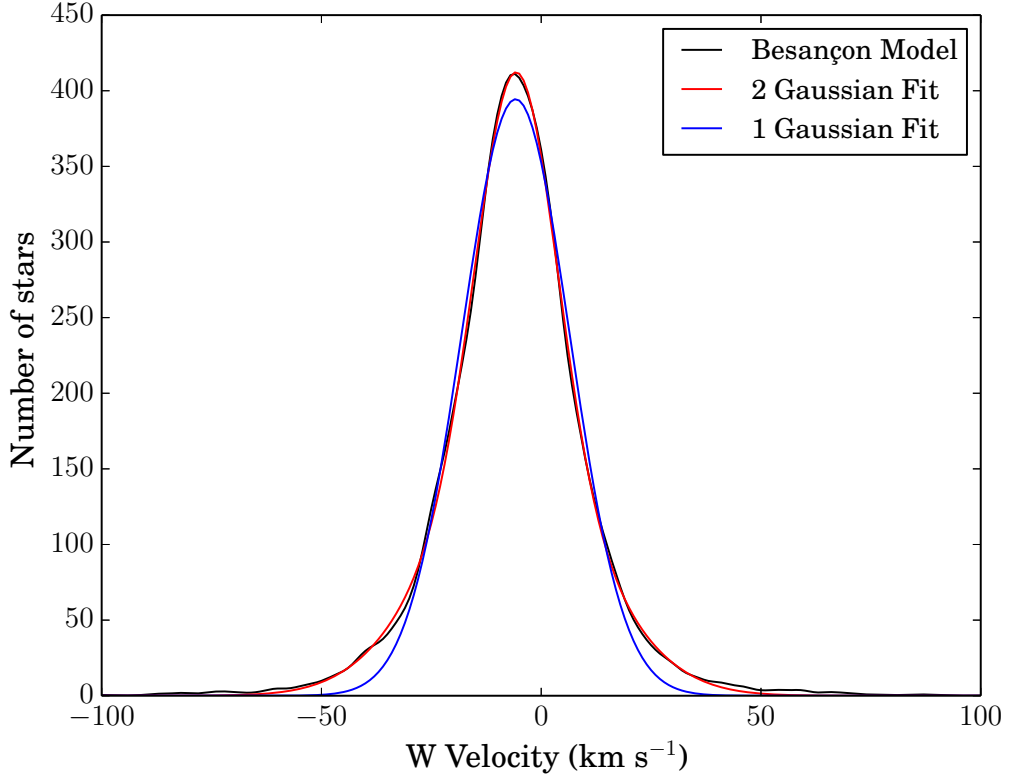


Figure 2.10: Generalized histogram representing the stars simulated using the Besançon model. The black curve shows the histogram and the red curve is the 2-component fit.

described earlier in this section. As before, we fit 2 Gaussians to the generalized histogram. The fit results are shown in Table 2.4.

	Cold Component	Hot Component	Single Gaussian Fit
Amplitude	45700 ± 400	12000 ± 500	55500 ± 300
Mean (km s^{-1})	-5.73 ± 0.03	-6.078 ± 0.16	-5.788 ± 0.062
Sigma (km s^{-1})	8.23 ± 0.05	19.79 ± 0.30	10.265 ± 0.062

Table 2.4: Results of the Gaussian fit for the luminosity weighted generalized histogram of the Besançon sample of stars. The amplitudes are in arbitrary units, as defined in Eqn. 2.1.

The total luminosity of each component is again proportional to the product $A\sigma$. Although the colder stars are fewer in number than the hotter stars, we find that their luminosity is a factor of 1.58 ± 0.06 higher than for the hotter stars. This younger and kinematically colder component would thus dominate the integrated light of a disc galaxy for which the star formation history of the thin disc was similar to that adopted in the Besançon model. We also tried to use similar methods to

obtain the luminosity ratio of the kinematically cold/hot stars from our sample (FF & BSC) of stars but with the luminosity weighting and the small sample size, we were not able to recover the older disc component of stars. The order of magnitude larger sample size of the Besançon simulation allowed us to derive the luminosity ratio without difficulty.

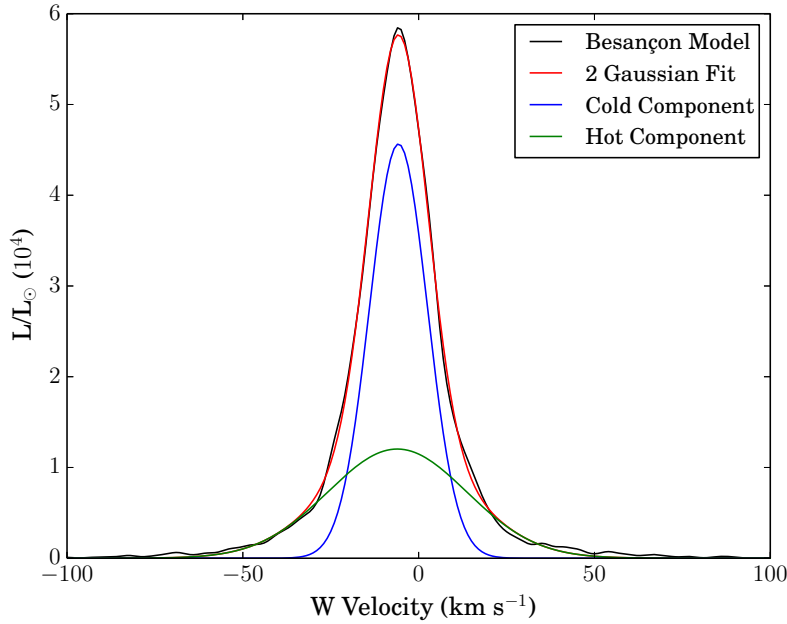


Figure 2.11: Generalized histogram of the W-distribution of the stars from the Besançon model. Each star contributed a Gaussian with area proportional to its luminosity and dispersion of 2 km s^{-1} . The red curve is the two component fit to the Besançon sample in black. The younger component and the older component are shown in blue and green respectively.

Fig. 2.12 shows the Besançon stars split by age into 2 samples. The young stars (age $\leq 2 \text{ Gyr}$) have a smaller dispersion of $8.24 \pm 0.01 \text{ km s}^{-1}$ and the older stars have a larger dispersion of $17.70 \pm 0.10 \text{ km s}^{-1}$, as expected.

2.6 Implications for External Galaxies

The Besançon simulations in the previous section looked at stars in a cone. In order to mimic observing the velocity distribution in external galaxies, we need a sample of stars in a cylinder perpendicular to the plane of the disc. We used the Besançon model to choose giants with spectral type G8III - K5III in the entire simulated sky, with $-3 \leq M_V \leq +3$ and $0.8 \leq B - V \leq 1.8$, within a distance of 5 kpc. We then selected giants in a cylinder of radius 2 kpc. This sample would be similar to what we would observe in the disc of a face-on galaxy from afar.

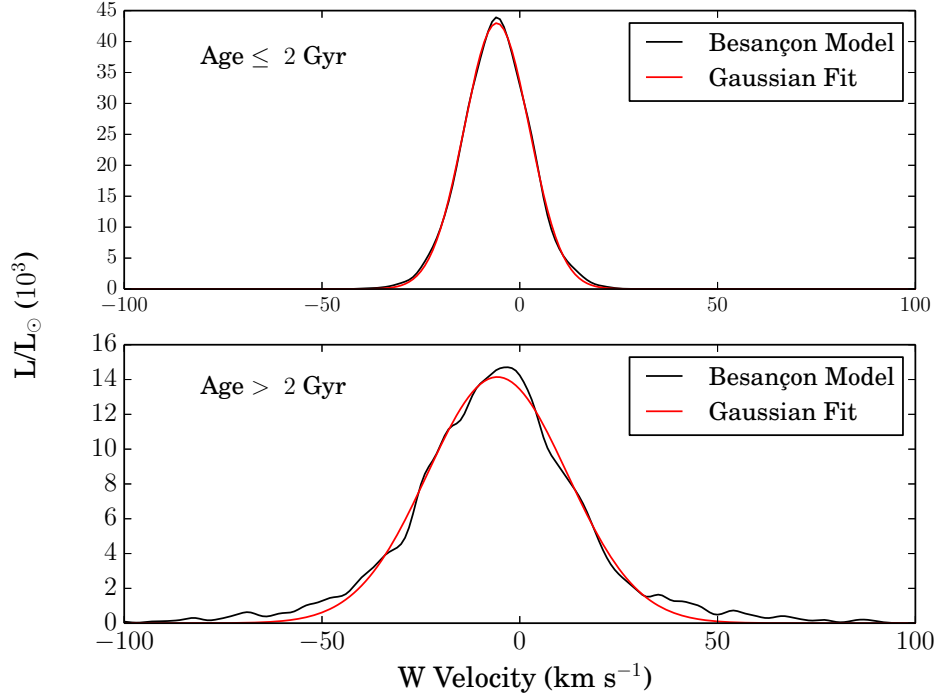


Figure 2.12: Generalized luminosity histogram of the W-distribution of the stars from the Besançon model based on age. The upper panel has all stars of age ≤ 2 Gyrs. These stars contribute the colder component with a narrow σ_W . The bottom panel shows the older stars that can be represented with a Gaussian with larger $\sigma \sim 18 \text{ km s}^{-1}$.

Fitting a double and single Gaussian to the luminosity-weighted velocity histogram of these sample of stars give us the results shown in Table 2.5. The fit is shown in Fig. 2.13. Using an analysis similar to that in Section 2.5, we find that the

	Cold Component	Hot Component	Single Gaussian Fit
Amplitude ($\times 10^3$)	2050 ± 26	650 ± 27	2633 ± 7
Mean (km s^{-1})	-5.96 ± 0.03	-5.81 ± 0.11	-5.93 ± 0.05
Sigma (km s^{-1})	13.0 ± 0.07	23.90 ± 0.30	15.40 ± 0.05

Table 2.5: Gaussian fit to the luminosity-weighted histogram of the Besançon sample of stars in a cylinder.

ratio of the estimated surface mass density of the disc between using the dispersion of the hotter thin disc component and using the dispersion for the single Gaussian fit, is:

$$\frac{\Sigma_2}{\Sigma_1} = \frac{\sigma_2^2}{\sigma_1^2} = \frac{(23.9 \pm 0.3)^2}{(15.40 \pm 0.05)^2} = 2.41 \pm 0.06 \quad (2.5)$$

As before, the subscript 1 refers to the single Gaussian fit and subscript 2 refers to

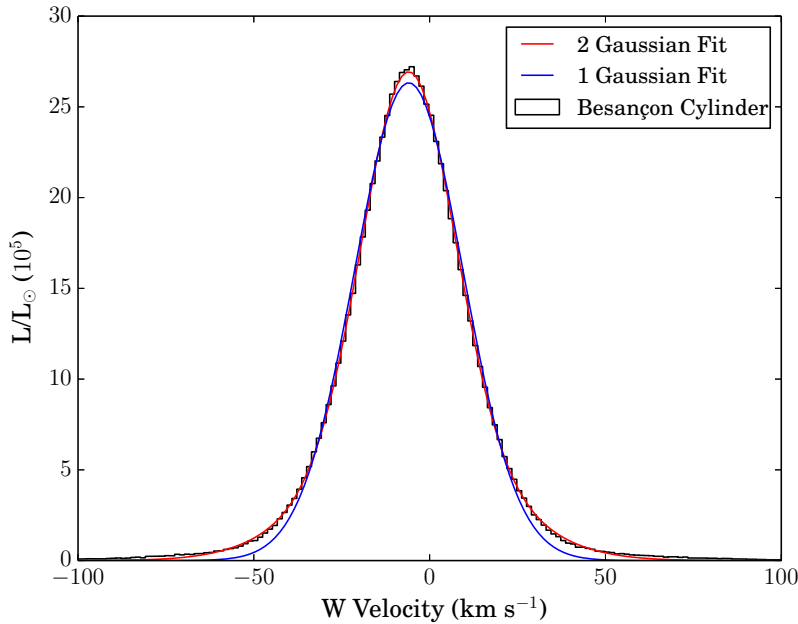


Figure 2.13: Luminosity-weighted histogram of the W-distribution of the stars from the Besançon stars in a cylinder. The double Gaussian fit is visibly better than the single Gaussian fit.

the hotter (older) component of the double Gaussian fit. The underestimation of the disc surface mass density in the cylindrical geometry is similar to the value that we got for our nearby sample of stars (see section 2.4).

The velocity dispersions that we calculated above are appropriate for a region with a similar star formation history and dynamical history as the solar neighbourhood. To get an idea of how the dispersions of the various components would change with a different star formation history, we constructed two different samples of stars: one with half the star formation rate over the last Gyr, and one with no star formation over the last Gyr. We again used a luminosity-weighted histogram to determine how the vertical velocity dispersions of the different Gaussian components would change. Our results are tabulated in Table 2.6. Although the hot and cold

	No star formation over last Gyr	Half the star formation over last Gyr
	σ (km s ⁻¹)	σ (km s ⁻¹)
Cold Component	14.06 ± 0.05	13.56 ± 0.06
Hot Component	27.74 ± 0.36	25.70 ± 0.33
Single Gaussian Fit	15.79 ± 0.05	15.61 ± 0.05

Table 2.6: Results of the Gaussian fit for the luminosity-weighted histogram of the Besançon sample of stars in a cylinder with different star formation histories.

components become slightly hotter as the recent star formation rate decreases, the dispersions for the single Gaussian fits change very little with the change in star

formation history. This reflects the age velocity relation adopted in the Besançon model.

2.7 Conclusions

Our analysis of W velocities of red giants in the solar neighbourhood shows the presence of two different population of stars – a kinematically hotter component with a dispersion of $18.6 \pm 1.0 \text{ km s}^{-1}$ and a kinematically colder component with a dispersion of $9.6 \pm 0.5 \text{ km s}^{-1}$. By number, the ratio of hot to cold stars in the solar neighbourhood is about 1.2:1, but this ratio would depend on the star formation history and dynamical evolution of the particular region that is under investigation. We note that the outcome of a simulated sample from the Besançon model, using similar selection criteria, is an excellent match to our stars both in the velocity dispersions and the ratios of hot to cold stars.

If we were to regard the giants as a single kinematically homogeneous population, and if we further assumed that the scale height of this population is the scale height derived statistically for the old disc of the galaxy, then we would underestimate the surface mass density of the disc by a factor of 2.05 ± 0.16 (section 2.4). We get a similar value of 2.41 ± 0.06 when looking at stars in a cylinder in the Besançon model (section 6). These assumptions are usually made in making kinematical estimates of the surface density of external disc galaxies. Again, this underestimate of a factor of 2 is appropriate for a region of a disc galaxy which has a similar star formation history and dynamical history to the Galactic disc near the sun. Using a velocity dispersion of 18.6 km s^{-1} and a scale height from literature, we obtain a disc surface density $\Sigma = 57 \pm 12 \text{ M}_{\odot} \text{ pc}^{-2}$, which is in fair agreement with the range of estimates calculated for the Milky Way in previous studies, using alternative techniques.

This work demonstrates an issue for studies that use the velocity dispersion of stars in the disc of external near-face-on galaxies to estimate their surface mass density. The scale height for these galaxies come from red or near-infrared photometry that is sensitive to the kinematically hotter population of disc stars. On the other hand, the integrated light spectroscopy that is used to estimate the vertical velocity dispersions includes contributions from both younger and older populations of stars. We have shown that the contribution of the kinematically colder stars to the integrated light of the solar neighbourhood may significantly outweigh the contribution from the kinematically hotter old disc, by a factor of about 1.56 in surface brightness. This factor is about 1.7 for the cylindrical sample from the Besançon Model (Section 2.6). The outcome would be a significant underestimate of the velocity dispersion of the old disc, and hence of the surface density of the disc. Thus a maximal disc would appear submaximal, and its dark halo will appear to have a shorter scale length and higher central density than its true value.

We can illustrate this effect quantitatively with a decomposition of the rotation curve of the spiral galaxy NGC 3198 which was studied in detail by van Albada et al. (1985). The upper panel of Fig. 2.14 shows a maximum disc decomposition similar to that shown in Fig. 2.4 of van Albada et al. (1985). We have used the disc model

of van Albada et al. (1985) and the widely used pseudo-isothermal-sphere (PITS) dark halo model with

$$\rho(r)/\rho(0) = [1 + (r/a)^2]^{-1}$$

for consistency with later work such as Kormendy & Freeman (2016). The rotation curve for the PITS dark halo model has the form

$$V_c^2(r) = V_\infty^2[1 - (\tan^{-1} x)/x],$$

where $V_\infty^2 = 4\pi G\rho(0)a^2$ and $x = r/a$. The adopted dark halo model parameters for the maximum disc decomposition are: $a = 7.45$ kpc, $V_\infty = 161$ km s⁻¹ and a central density $\rho(0) = 0.0086 M_\odot \text{ pc}^{-3}$. Although our dark halo model is slightly different from the model used by van Albada et al. (1985) (both have constant density central cores), the halo V_c curves are almost identical. The lower panel of Fig. 2.14 shows the decomposition for a disc surface density that is lower by a factor 2 than the one shown in the upper panel. This decomposition and the maximum disc decomposition are equally satisfactory, illustrating the disc-halo degeneracy, but the amplitude of the rotation contribution for the disc is now lower by $\sqrt{2}$ and the required halo has a much shorter scale length a and higher central density $\rho(0)$. The halo model shown in the lower panel of Fig. 2.14 has $a = 1.5$ kpc, $V_\infty = 144$ km s⁻¹ and $\rho(0) = 0.17 M_\odot \text{ pc}^{-3}$. In summary, if a disc of a galaxy like NGC 3198 is truly maximal and its surface density is underestimated by a factor of 2, as we believe could follow from adopting a single velocity dispersion for the young and old giants, then the central density of its dark halo would be overestimated by a factor of about 20 and its scale length a would be underestimated by a factor of about 5. This would introduce a serious distortion into the scaling laws for dark haloes (see e.g. Kormendy & Freeman 2016).

In order to handle the problem of kinematical inhomogeneity described here, we undertook a program to measure the velocity dispersion of the old disc of several large nearby disc galaxies, by making (i) a two-component analysis of the integrated light spectra of regions in their discs, and (ii) measuring radial velocities for large numbers of planetary nebulae in their discs. As for the red giants, the planetary nebulae have progenitors of a wide range of ages, and we can expect them to include kinematically hot and cold sub-components. The next chapter describes the instruments we used to carry out the observations of these external disc galaxies.

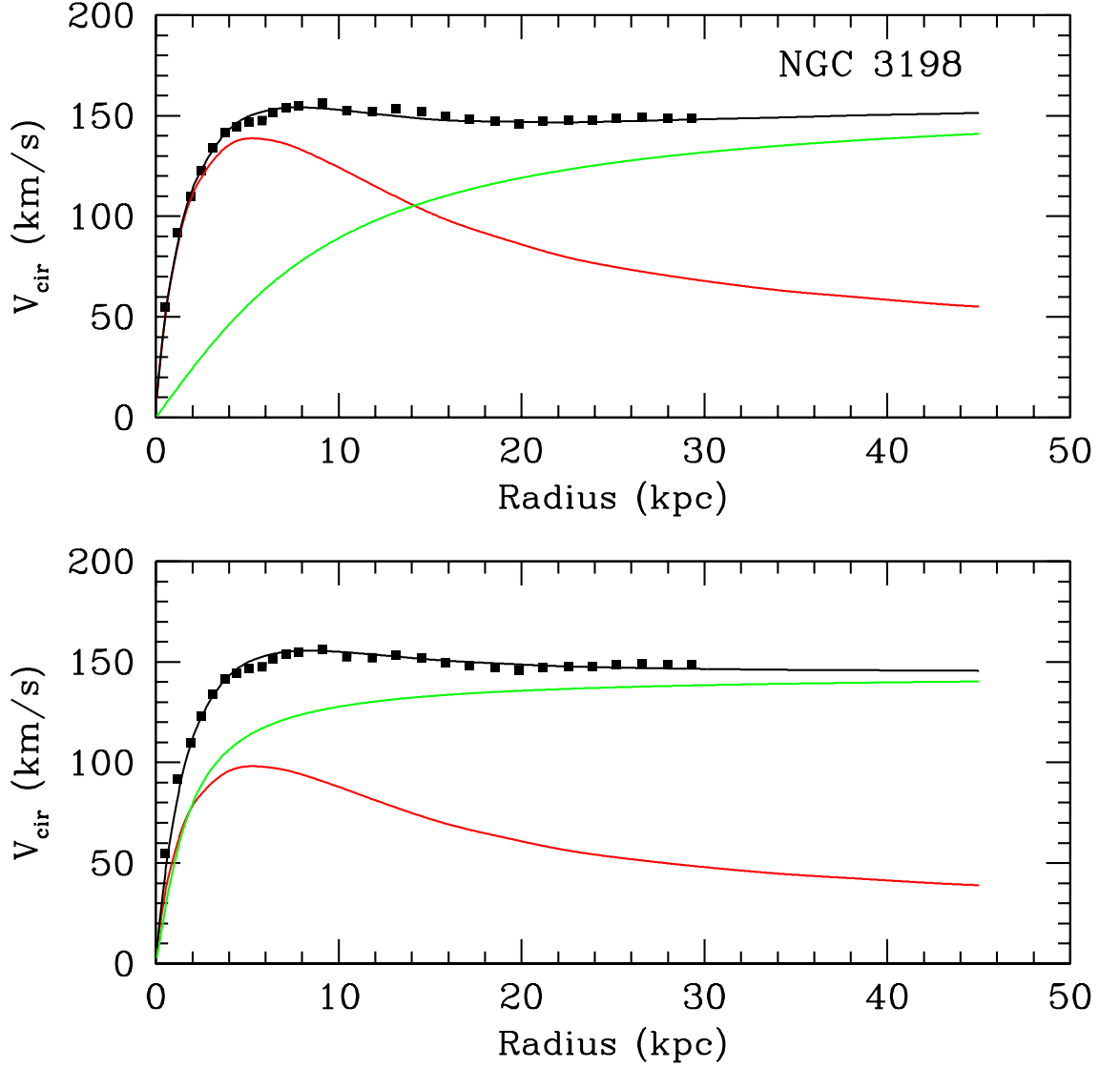


Figure 2.14: Upper panel shows a maximum disc decomposition of the rotation curve of NGC 3198. Rotation data (black squares) and the rotation curve for the maximum disc (red curve) are adapted from van Albada et al. (1985). The green curve shows the rotation curve for the required halo, and the black curve is the total rotation curve from disc + halo (see section 7 for details). Lower panel shows the decomposition for a disc with surface density = 0.5 of the maximum disc value. The required dark halo is now much more compact: its central density is about 20 times higher than for the maximum disc decomposition and its scale length is about 5 times shorter.

INSTRUMENTS

Our study of the K-giants in the solar neighbourhood (as discussed in the previous chapter) concluded that there were two population of stars in the solar neighbourhood – the older, kinematically hotter stars with larger vertical velocity dispersions and the younger, kinematically colder population of stars with smaller velocity dispersions. We established that failing to extract out these two (very different) dispersions will lead to erroneously concluding that galaxy discs are submaximal. The next step in the project is to study a sample of external galaxies, whose rotation curves are readily available, to break their disc-(dark halo) degeneracy. We use integrated light spectra and velocity distributions of individual planetary nebulae to derive the velocity dispersions of the hot and cold components of the discs in a few nearby disc galaxies.

We identified four nearby, near face-on galaxies to observe for this project. We also identified two different instruments that are best suited for this project – the VIRUS-W (acronym stands for Visible Integral field Replicable Unit Spectrographs – Wendelstein) spectrograph which analyzes the absorption spectra of our target galaxies in the inner 1 - 1.5 scale length and the PN.S (acronym stands for Planetary Nebula Spectrograph) instrument, which is an imaging spectrograph, that uses planetary nebulae (PNe) as dynamical tracers of the galaxy out to radii > 4 scale lengths. This chapter discusses the main technical details of these instruments and their capabilities that make them ideal for this project.

3.1 VIRUS-W

The VIRUS-W is an instrument developed by the University Observatory of the Ludwig-Maximilians University and the Max-Planck Institute for Extraterrestrial Physics in Munich, Germany. It is an improved version of the the Mitchell Spectrograph (formerly VIRUS- P; Hill et al. 2008) . The VIRUS-W instrument was built in 2010. It is currently in operation on the 2.7m Harlan J. Smith Telescope at McDonald observatory in Texas.

3.1.1 Instrument Design

The VIRUS-W is an optical-fibre-based Integral Field Unit (IFU) spectrograph with 267 fibres, each 150 μm -core optical fibers with a fill factor of 1/3. With a beam of

$f/3.65$, the core diameter corresponds to $3.2''$ on sky, and the instrument has a large field of view of $105'' \times 55''$ (Fabricius et al. 2012). The instrument has two modes: a high resolution mode with a spectral resolution of $R \sim 8700$ or an average velocity resolution of about 14.7 km s^{-1} (gaussian sigma of the PSF) and low resolution mode with $R \sim 3300$. We only make use of the high resolution mode, since from the work on the solar neighbourhood, we expect the cold component to have a low dispersion $\sim 10 \text{ km s}^{-1}$. The high resolution mode has a spectral coverage of $4802 - 5470 \text{ \AA}$. The instrument is ideally suited for the study of the absorption features in the Mgb region ($\sim 5175 \text{ \AA}$). Fig. 3.1 shows the micrograph of the IFU with the 267 fibres.

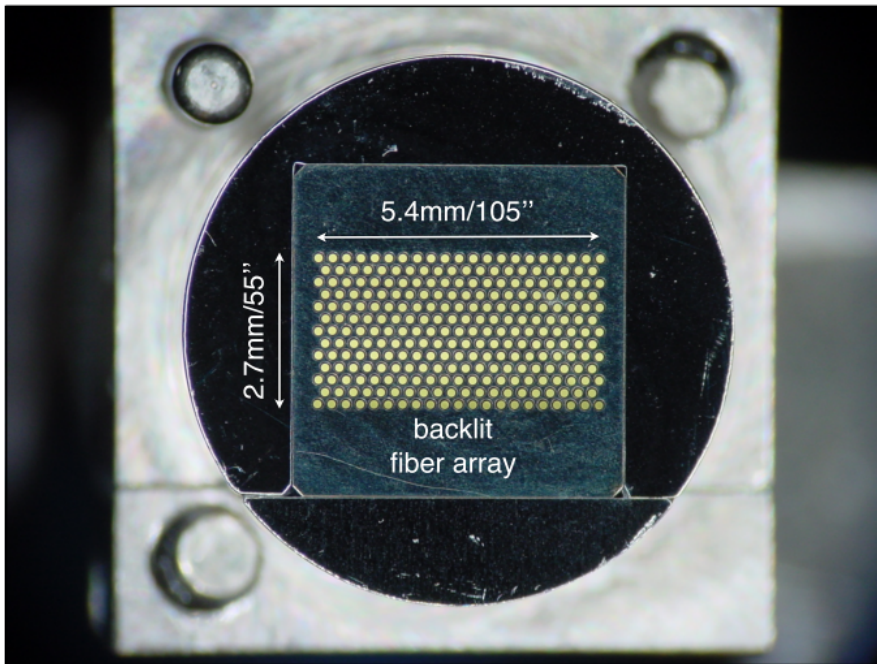


Figure 3.1: The micrograph of the IFU showing the 267 fibres arranged in a hexagonal densepack scheme. Image taken from Fabricius et al. (2012).

The layout of the spectrograph is shown in Fig. 3.2. The spectrograph uses an inverse Schmidt type design for the collimation of the light. The light enters the spectrograph through the 267 fibres, which are spread out into a 76 mm long pseudo slit. The pseudo slit faces a spherical collimator that reflects the light back in the direction of the optical fibres which then reflects the light to the dispersive element. In the high resolution mode two large prisms and a 3300 l/mm VPH grating act as dispersive element. This grating offer a high throughput with very little scattered light. The spectra is recorded by a 200mm aperture, $f/1.4$ camera. The high resolution grating has a peak value of 70% and an impressive diffraction efficiency, which is responsible for the very high instrumental throughput (Fabricius et al. 2012). A Marconi (e2v) CCD44-82 back side illuminated CCD with 2048×4096 15m square pixels. Its quantum efficiency is $\sim 80\% - 85\%$ with a mean value of 83% in the covered spectral range ($\sim 4802 \text{ \AA} - 5470 \text{ \AA}$). The camera head is mounted at the lens exit with three fine threaded screws to allow to adjust for tip

tilt and piston. It is decoupled from the lens and equipped with its own vacuum window. The detector is read out over two amplifiers at 110kHz with a gain of 1.61 ADU/e⁻ and a read noise of 2.55 e⁻. The spectrograph is mounted on a 1600mm × 1200 mm optical bench at the McDonald Observatory. The control room, where the instrument is placed, is temperature controlled. This results in high instrument stability.

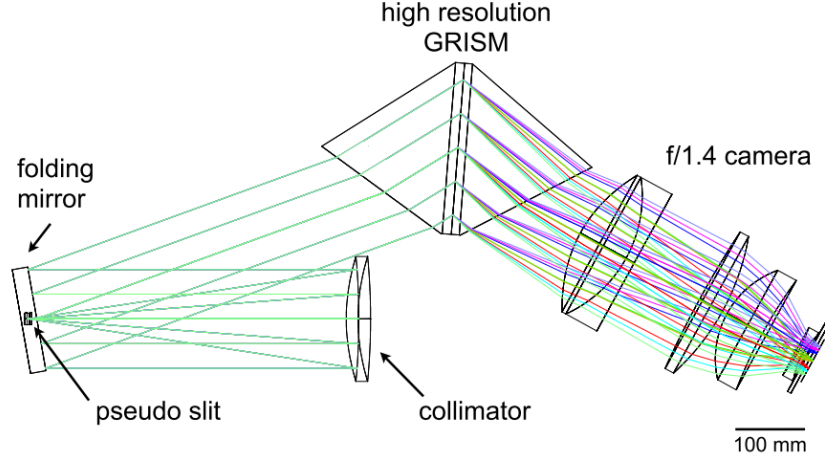


Figure 3.2: Layout of the spectrograph in the high resolution mode (see text for details). Image taken from Fabricius et al. (2012).

3.1.2 CURE Reduction Pipeline

The raw data were reduced using the automated pipeline ‘CURE’ which was originally developed for HETDEX, but later adapted for VIRUS-W data reductions. The pipeline uses the biases and dome flats obtained during observation to debias and flat field correct the raw data. The pipeline then uses the observed arc frames for the wavelength calibration of the images. The final step is extraction of the spectrum from each fibre and then subtracting the sky. To get accurate sky subtraction, we observed a (sky, galaxy, sky) sequence, with equal exposure time for each frame, for each field that we observed. The sky frames preceding and succeeding the galaxy image are averaged and scaled to match the exposure time of the galaxy frame, which is then subtracted from the galaxy image. The data were reduced in log-wavelength space. The velocity step of the spectrum is $\sim 11 \text{ km s}^{-1}$. As a check on the stability of the instrument, we combined all of our sky images (obtained while observing the galaxy NGC 628) to produce a 2D sky image with very high counts. We then measured the wavelengths of some known sky emission lines in the 1D spectrum from one of the fibres in this 2D image and compared them with the Osterbrock et al. (1996) wavelengths. This comparison is shown in Table 3.1. Since the positions of the emission lines in this spectrum match the known values, we cross-correlated the other 266 fibre spectra with this spectrum to see if there are any significant shifts in the wavelength solution. The shifts obtained from the

correlation peak are all $< 2 \text{ km s}^{-1}$. Thus the VIRUS-W is a very stable instrument and the errors in the wavelength system make a negligible contribution to the error budget.

Measured Wavelength (Å)	Osterbrock Wavelength (Å)
5202.89	5202.98
5238.81	5238.75
5255.97	5256.08

Table 3.1: Comparison between the measured wavelengths of the sky lines from one of the fibres of our combined sky spectrum and the values from Osterbrock et al. (1996). This fibre was then cross-correlated with the other fibres to check for any large wavelength shifts. The shifts were all $< 2 \text{ km s}^{-1}$, indicating that errors in the wavelength system make a negligible contribution to the error budget.

3.1.3 Instrumental Capabilities

The instrumental resolution of the VIRUS-W in the high resolution mode $\sim 14 \text{ km s}^{-1}$. However, from our solar neighbourhood work, we expect the vertical velocity dispersion of the cold component $\sim 10 \text{ km s}^{-1}$. If we intend to be able to separate out the observed spectra from our galaxies into the cold young component and the hot old component, our instrument should be capable of measuring these expected low dispersions. Obtaining high signal-to-noise ratio (SNR) should, in principle allow us to measure dispersions lower than the average instrumental dispersion. In order to test the feasibility of using VIRUS-W for this project, we decided to obtain high SNR spectra of globular clusters known to have dispersion values $< 10 \text{ km s}^{-1}$.

We obtained data on two globular clusters: M2 (NGC 7089) and M15 (NGC 7078). These data were obtained during an observing run in October 2014. Table 3.2 gives the details of the observations. We looked at the central regions of these clusters to measure the σ_{LOS} , which we can compare to literature values. Fig. 3.3 shows the positions of the VIRUS-W fibres on the globular clusters. We obtained 4 (sky, object, sky) sequences, which were reduced using the standard reduction procedure. The spectrum from each of the fields were summed up to create a final high SNR spectrum for each globular cluster.

Name	RA (J2000)	Dec (J2000)	Exposure Time (s)	SNR
M2	21:33:27	−00:49:24	4×800	149
M15	21:29:58	+12:10:01	4×700	213

Table 3.2: Details of the VIRUS-W observations for M2 and M15. The SNR quoted are per resolution element for the final summed up spectrum. We expect an SNR of at least 60 in each of our galaxy fields.

I used the penalized pixel-fitting code (pPXF) developed by Cappellari & Emsellem (2004) to get the mean velocity and velocity dispersion from the spectra of

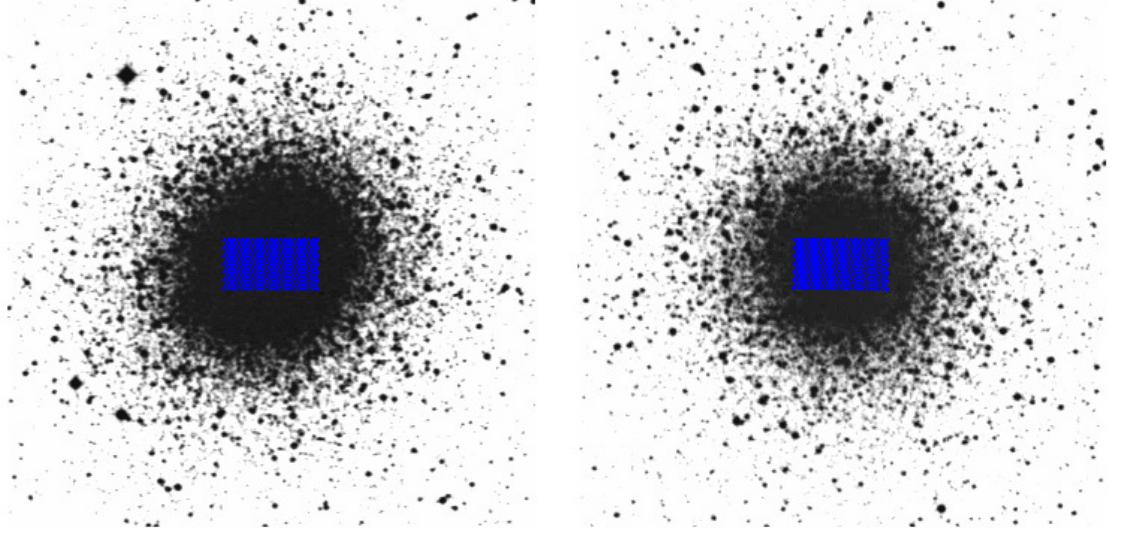


Figure 3.3: The position of the VIRUS-W IFU fibres on M2 (left) and M15 (right).

M2 and M15. Fig. 3.4 shows the best fit spectra found by pPXF for the two clusters. The results are tabulated in table 3.3 and compared with literature values from Harris (1996). Our values are very close to the previous estimates of velocity and σ_{LOS} . Our errors are the 1σ errors obtained from monte carlo simulations. More importantly, we ensure that VIRUS-W can measure very low dispersion values ($< 10 \text{ km s}^{-1}$). This is imperative to being able to measure the low dispersion values expected from the kinematically cold thin disc component.

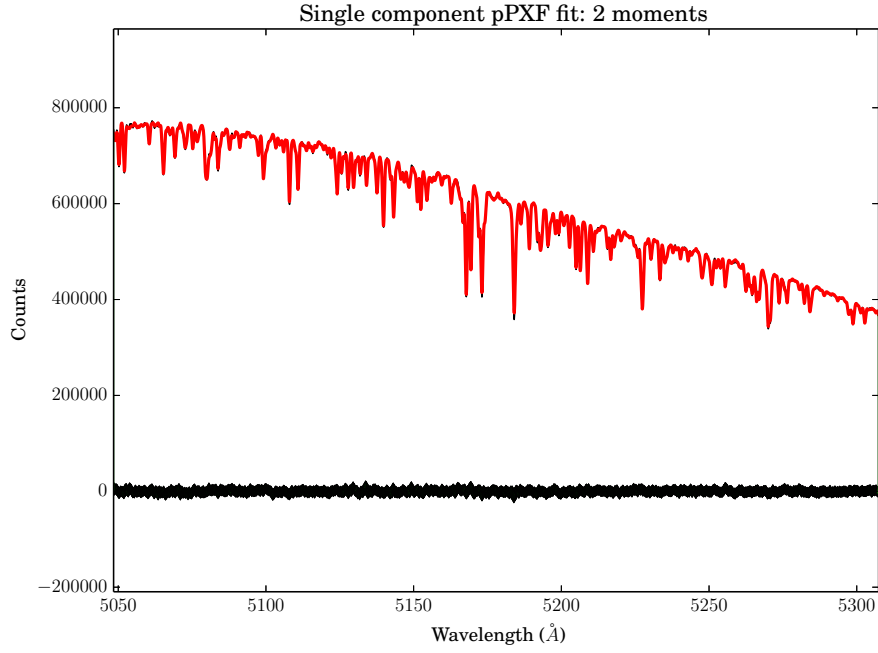
Name	Our results		Literature values	
	Velocity (km s^{-1})	σ_{LOS} (km s^{-1})	Velocity (km s^{-1})	σ_{LOS} (km s^{-1})
M2	-5.1 ± 0.3	9.4 ± 0.5	-5.3 ± 2.0	8.2 ± 0.6
M15	-102.2 ± 0.4	10.6 ± 0.5	-107.0 ± 0.2	13.5 ± 0.9

Table 3.3: The heliocentric velocities and dispersions that we find from our analysis compared with the results from Harris (1996).

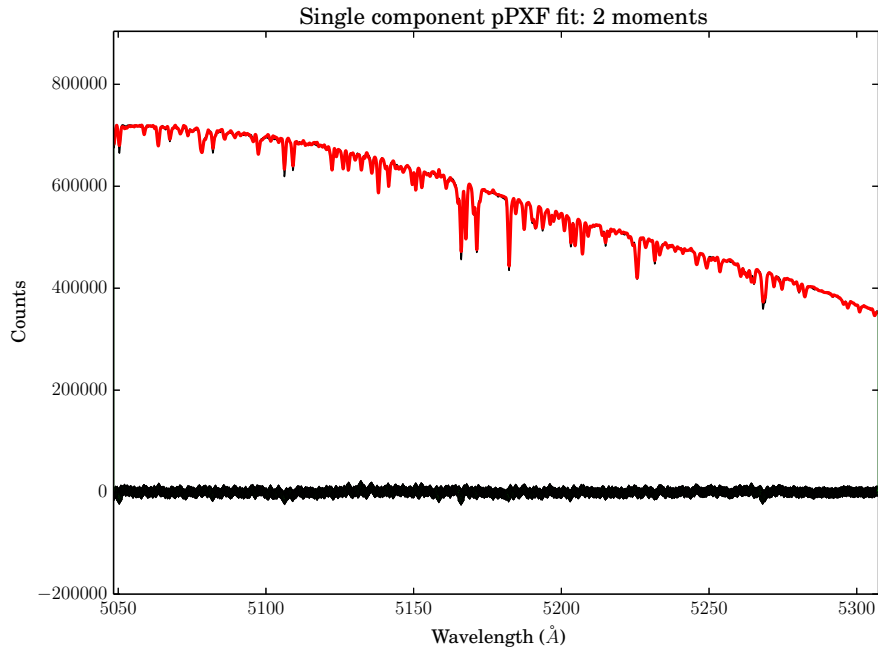
Thus, due to its high resolution and instrumental stability, VIRUS-W is the ideal spectrograph for this project.

3.2 Planetary Nebula Spectrograph

Planetary nebulae (PNe) have been used to extend stellar kinematical studies in external galaxies to larger radii, where the dark matter is expected to dominate the potential (Douglas et al. 2007). The planetary nebula spectrograph (PN.S) is an imaging spectrograph designed for efficient observation of extragalactic PNe, and is



(a)



(b)

Figure 3.4: The pPXF fit results for (a) M2 and (b) M15. Only the high resolution Mgb region of the spectrum was used for the fit. The cluster spectrum is in black, which is overplotted with the best fit from pPXF in red. The residuals are shown at the bottom in dark green.

used for the present project. It operates on the 4.2 m William Herschel Telescope at La Palma, and has a field of view of 10.4×11.3 arcmin². The PN.S has a 'left' and 'right' arm in which the light is dispersed in opposite directions. Combining these two counter-dispersed images allows the PNe to be detected and their radial velocities to be measured in a single observation. The PN.S also has an undispersed H α imaging arm which can help to distinguish HII regions and background Ly α emitters from the PNe.

The PN.S is used by the PN.S collaboration (PI: M. Arnaboldi), so far mainly on early-type galaxies plus a study of PNe in M31 (Merrett et al. 2006). This is the first PN.S project to look at a sample of nearby face-on galaxies, aimed at measuring the internal kinematics of the discs in an attempt to break the disc-halo degeneracy.

3.2.1 Left and Right [OIII] arms

The PN.S uses narrowband slitless spectroscopy by obtaining two sets of data with the spectra dispersed in different directions: a technique referred to as counter-dispersed imaging (Douglas et al. 2002). PNe have strong characteristic emission lines, with the brightest line being the 5007 Å line of [OIII], in which up to 15% of the central stars energy is emitted (Dopita et al. 1992). Fig. 3.5 shows the schematic

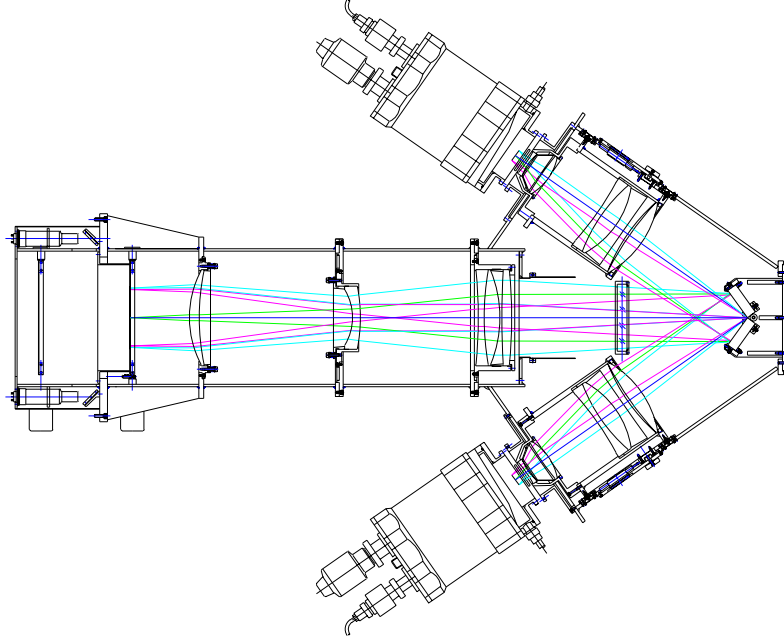


Figure 3.5: The optical arrangement of the PN.S showing the left and right [OIII] arms. The pair of diffraction gratings on the right split the light beam into the two identical spectrograph arms, each with opposite dispersion directions.

setup of the left and right [OIII] arms of the PN.S. A pair of diffraction gratings split the light entering the telescope into the two [OIII] arms. These arms are fitted with a narrow band [OIII] filter and essentially survey the same field, but the dispersion

direction is reversed. Thus for each field surveyed, we get a left and right image dispersed in opposite directions, in which the continuum sources like stars in the field appear as short streaks of spectrum. The PNe on the other hand appear as unresolved objects, due to their strong [OIII] emission (Douglas et al. 2002). The radial velocity of the PNe causes its left and right images to be displaced. Therefore, measuring the separation in the position of an identified PN on the left and right images is a measure of the PN's radial velocity.

3.2.2 $H\alpha$ arm

The initial design of the PN.S only included the left and right [OIII] arms. An $H\alpha$ arm was added later to increase accuracy in discriminating between PNe and HII regions when studying late type galaxies. For the PNe that are detected in $H\alpha$, the $H\alpha$ image constitutes a cross-check of the velocity measurement. The image will also serve as a check on the astrometric procedures used on the counter-dispersed images and as an indicator of contaminating objects (Douglas et al. 2002). HII regions are a major source of contamination in spiral galaxies, because they also emit strong [OIII] emission lines. Typically a ratio of the $H\alpha$ /[OIII] flux is used in discriminating between PNe and HII regions (Ciardullo et al. 2002).

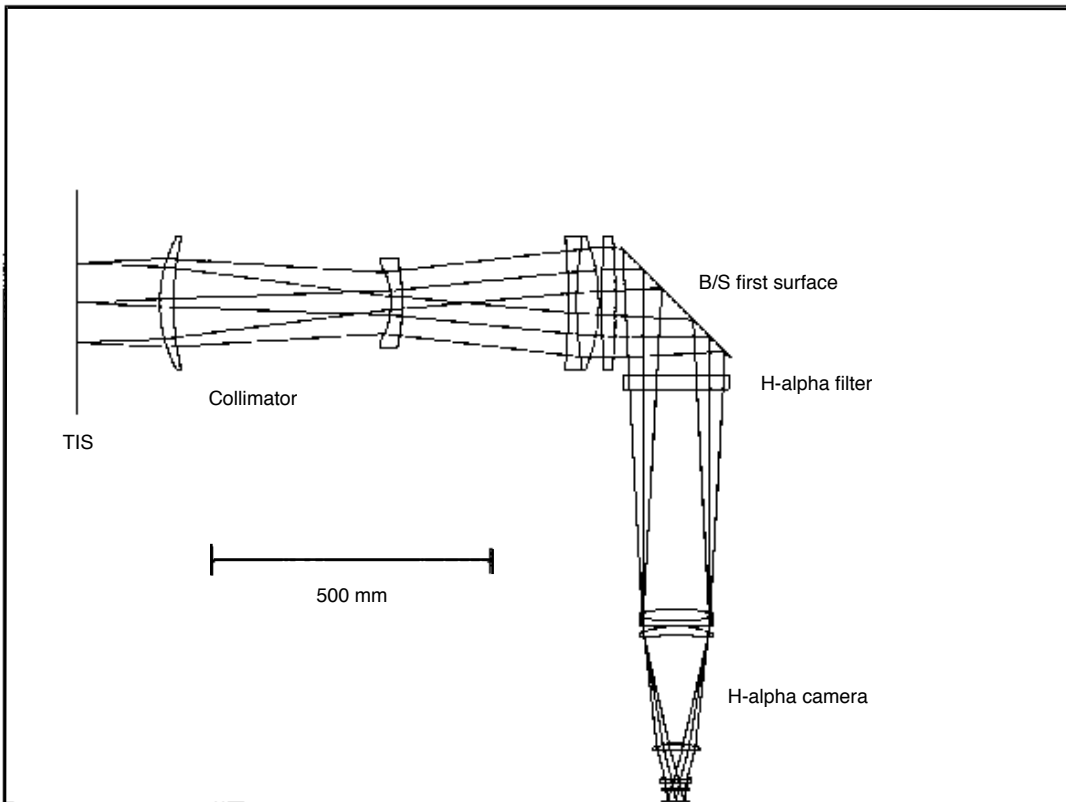


Figure 3.6: The optical arrangement of the PN.S showing the $H\alpha$ arm. B/S is the beam splitter, and the optics to the left of the B/S are the standard PN.S optics.

The $H\alpha$ arm is a simple imaging arm. Its axis is perpendicular to the axis of the

[OIII] arm, and is fed by a dichroic beam splitter which sits in the collimated beam ahead of the [OIII] gratings. Then there is a filter holder for the $H\alpha$ and R-band filters, and the camera and the CCD. Fig. 3.6 shows the optical arrangement for the $H\alpha$ arm of the PN.S. The $H\alpha$ arm consists of a narrow band $H\alpha$ filter, as well as a broad R-band filter.

3.2.3 Reduction Pipeline

The automated reduction code for the PN.S is a combination of IRAF and FORTRAN scripts. A detailed description of how the reduction script works can be found in Douglas et al. (2007) and Arnaboldi et al. (2017). The code debiases and flat-field corrects the raw images from the left and right arms (L and R below), using bias frames and flats obtained during the run. Cosmic rays are removed using a custom-built routine in the pipeline.

The most important step in the reduction code is the wavelength calibration. The arc images are obtained by illuminating with a dispersed Cu-Ne-Ar lamp. Our bandpass includes four arc lines at wavelengths of about 5009 Å, 5017 Å, 5031 Å and 5038 Å. An automated task called 'alignspots' identifies and centroids the spots on the CCD and fits a joint polynomial fit for position and wavelength. For this project, we drastically improved the efficiency of alignspots by applying a higher order geometric distortion correction. This is especially important when our aim is to extract the very low dispersions expected for the cold component. The solution represents a map from positions in the sky reference frame (X, Y) and wavelength (λ) to the (x, y) position on the CCD: $\{x, y\} = f\{X, Y, \lambda\}$. The two counter-dispersed arms of the PN.S provide two independent mappings to positions on the two CCDs. For pairs of detected sources on the (L,R) CCDs, this mappings can be uniquely inverted to transform $\{x_L, y_L, x_R, y_R\}$ to $\{X, Y, \lambda\}$. These mapping functions also allow us to correct spatial distortions introduced by the spectrograph and transform the images to "true" sky coordinates, using the IRAF commands geomap and geotrans (Douglas et al. 2007). The velocities of the PNe are evaluated using a rest wavelength of the [OIII] line of 5006.8Å (Douglas et al. 2007).

The left and right images obtained for a field are then stacked to create the final galaxy image. The image with the best seeing is chosen as the reference image, on which the rest of the images are registered. The USNO B1 catalogue is used to get the position of $\sim 15 - 20$ stars in the field of view. While the PNe appear on the CCDs as unresolved dots of [OIII] emission, the stars appear as short dispersed spectra, and their positions are used as reference images to correct for relative offsets and combine the images. The stars also provide an absolute astrometric reference frame for the images.

This was the first project that made use of the $H\alpha$ arm. All our target galaxies were observed simultaneously in $H\alpha$, using the $H\alpha$ narrow band filter on the undispersed $H\alpha$ arm of the PN.S. Since this study is the first that makes use of the $H\alpha$ data in its analysis, the reduction pipeline for reducing the $H\alpha$ images was written from scratch using standard IRAF packages and standard techniques. First, we debias and flat field correct the raw $H\alpha$ images. Then a reference image is identified for

all the images in a field to be stacked on. The image with the best seeing is usually adopted as the reference image. The positions of a few stars on the reference image are identified. This is used to identify the same stars in the other images, so that they can be shifted and stacked together, such that there is no offset between any of the images. We then identified a dss image of the same field as the $H\alpha$ image and used the RA/Dec information in the dss image to get the astrometry of the $H\alpha$ image. We used the IRAF packages ccmmap to get the plate solutions, and the package ccsetwcs to add the wcs information into the header of the $H\alpha$ image. We now have stacked images for the [OIII] left and right arms as well a corresponding stacked $H\alpha$ image for the same field.

3.2.4 Source Identification

After the [OIII] and $H\alpha$ have been stacked, the next step is to identify the PNe. Identification of PNe in late type galaxies brings in a new set of challenges, due mainly to contamination from HII regions. HII regions can also have strong [OIII] emission, and it is important to distinguish them from true PNe candidates. We use SExtractor to identify all unresolved objects in the left and right [OIII] images, and the $H\alpha$ image. However, this is a mix of PNe as well as HII regions. It is important to separate out the 'true PNe' candidates in order to proceed with our analysis. We use the example of NGC 628 (the first galaxy that we analysed) to explain how we go about extracting a catalogue of PNe candidates.

3.2.4.1 Colour-Magnitude cut

In NGC 628, we identified 635 unresolved objects that were detected in both the [OIII] and $H\alpha$ images. Our pipeline returns instrumental magnitudes for each of the identified objects in the [OIII] band and $H\alpha$ band. We need to convert this to the standard m_{5007} magnitude scale to be able to compare our analysis with previous studies. We use spectrophotometric standard stars to convert our instrumental magnitudes to m_{5007} values. While using them for calibration, we checked the wavelength solution near the location of the standard star spectra and also the passband of the filter. At the location of the [OIII] line for NGC 628 objects, the pixel scale in the direction of dispersion is $0.769 \text{ \AA pixel}^{-1}$ or $1.30 \text{ pixel \AA}^{-1}$. At the same location, the half-power wavelengths for the filter passband are 4999 and 5043 $\text{\AA}$. The wavelength of [OIII] emitters in NGC 628 is about 5018 $\text{\AA}$, which is near the midpoint of the filter passband. The passband for the hot standard stars is quite symmetrical.

The instrumental magnitude m_0 is defined as $m_0 = 2.5\log(\text{counts(ADU s}^{-1}\text{)})$, corrected to outside the atmosphere. We also calculate the mean conversion factor (Douglas et al. 2007), which represents the photon energy flux incident outside the atmosphere per CCD electron count rate, in units of $\text{erg cm}^{-2} \text{ s}^{-1}$ per (CCD electron s^{-1}). We adopt an atmospheric extinction coefficient $k_{5007} = 0.17$ at the observed wavelength of the [OIII] line, based on a mean value of k_V at the WHT site. From

the standard star observations, the calibration of m_0 to m_{AB} is:

$$m_{AB} = m_0 + (18.01 \pm 0.12)$$

For f_λ (erg cm² s⁻¹ Å⁻¹) at the observed wavelength of 5007 Å,

$$m_{AB} = -2.5 \log f_\lambda - 20.90$$

The m_{5007} magnitude is defined by:

$$m_{5007} = m_0 + 25.16$$

From the above equations, m_{5007} and our instrumental magnitude are related by:

$$m_{5007} = m_0 + 25.16 \quad (3.1)$$

Using the nominal gain of the CCDs (1.16 e⁻ ADU⁻¹), the mean value of the conversion factor, averaged over the two sides of the PN.S, is 2.34×10^{-16} . Douglas et al. (2007) found a mean value of 2.07×10^{-16} . We can now estimate our expected instrumental magnitude m_0 for the bright end of the PNLf in NGC 628, on which we can base the selection of PNe in NGC 628. The distance modulus of NGC 628 is 29.8 (from NED) and the bright end of the PNLf is nominally at an absolute magnitude $M_{5007} = 4.5$ or $m_{5007} = 25.3$ or $m_0 = 0.1$.

Direct comparison of the Herrmann & Ciardullo (2009b) magnitudes with our m_0 magnitudes for a sample of PNe in NGC 628 gave:

$$m_{5007}(H\&C) = m_0 + 24.64 \quad (3.2)$$

There is a ~ 0.5 mag discrepancy between Eqn. 3.1 and Eqn. 3.2. The origin of this discrepancy is unclear. We use Eqn. 3.1 to calculate the bright luminosity cut-off for our sample. Where Herrmann & Ciardullo (2009b) data are available, we use Eqn. 3.2 to convert our magnitudes to their scale for direct comparison of the kinematic results.

Herrmann & Ciardullo (2009b) use the [OIII]-H α emission line ratio to discriminate between PNe and HII regions, as described in Ciardullo et al. (2002). We decided to directly compare all our identified sources to the objects identified as PNe by Herrmann & Ciardullo (2009b) in NGC 628. NGC 628 is the ideal galaxy for this comparison, since among our target galaxies, it is the one with the largest PNe identified by Herrmann & Ciardullo (2009b). Fig. 3.7 shows the colour-magnitude plot for our sample compared with the objects we have in common with the Herrmann & Ciardullo (2009b) sample.

The colour is calculated as: $m_0 - m_{H\alpha}$ i.e the difference between the instrumental [OIII] magnitude and the instrumental H α magnitude. In Fig. 3.7, the x-axis is the m_{5007} obtained using Eqn. 3.2. The black points are our data for NGC 628, and the magenta open circles are the Herrmann & Ciardullo (2009b) PNe data for the same galaxy. The red lines show the split between our PNe and HII regions. All

objects to the right of this split are what we consider to be the 'true PNe' in this galaxy. An object has to satisfy the following two criteria in order to be considered as a PN:

$$\begin{aligned} m_{5007} &\geq m_{5007}^* \\ \text{colour} &\leq 3.2(m_{5007} - m_{5007}^*) + 1.706 \end{aligned} \quad (3.3)$$

where m_{5007}^* is the bright luminosity cut-off for the galaxy.

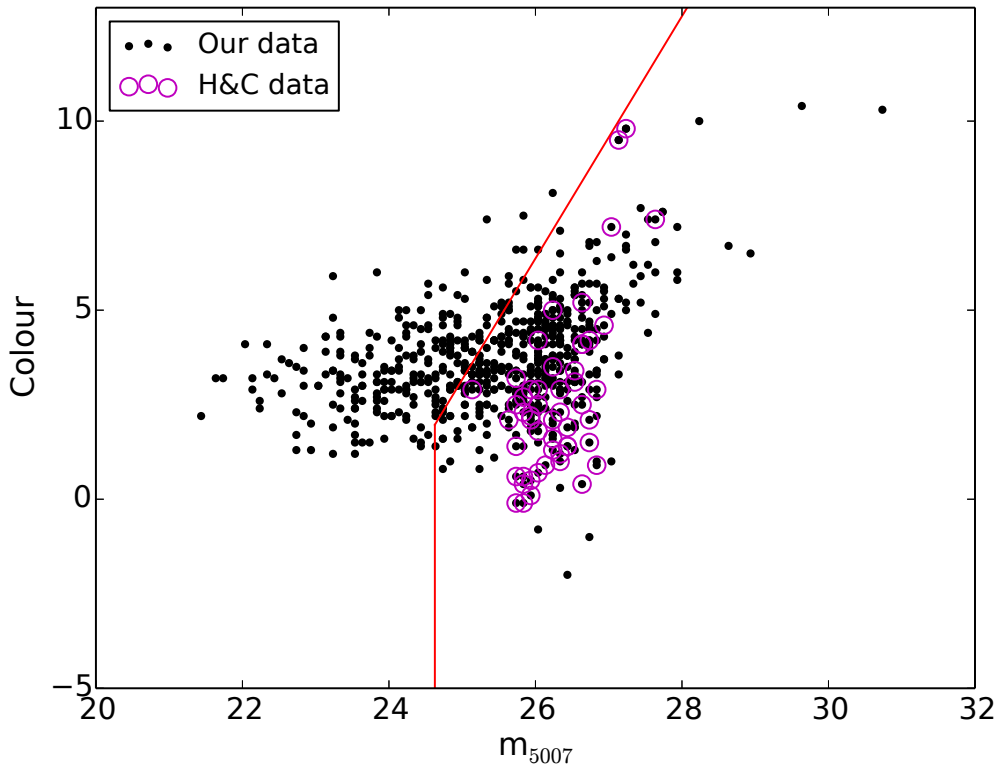


Figure 3.7: Colour-magnitude cut to separate PNe from HII regions. The black points are all our identified [OIII] sources in NGC 628. The magenta circles are the objects identified by Herrmann & Ciardullo (2009b) as bonafide PNe. The red lines denote the cut that we use to separate out the fainter PNe from the brighter HII regions.

We use this relation to separate out the PNe candidates from the HII regions in all our galaxies. the HII regions contaminating the sample are likely to have low velocity dispersions and would fall into the velocity distribution of the young component. They are unlikely to affect the dispersions of the hot component, which is the parameter that we are interested in. The following chapters discuss in detail the analysis involved in getting the kinematics for the two (hot and cold) components and their implications for rotation curve decomposition

NGC 628

4.1 Introduction

NGC 628 (M74) is a nearby ($D = 8.6$ Mpc), almost face-on galaxy. It is the most face-on galaxy in our sample which presents an advantage while trying to extract the vertical velocity dispersion (σ_z) from the line-of-sight dispersion (σ_{LOS}). The more face-on a galaxy is, the bigger contribution that σ_z provides to the σ_{LOS} , and the less contribution from the other in-plane dispersion components. Another advantage of using near face-on galaxies is that the contributions from the asymmetric drifts of the hot and cold populations are minimal.

As discussed in Chapter 1, using the 1D Jeans Eqn. in the vertical direction, the vertical luminosity-weighted velocity dispersion σ_z (integrated vertically through the disc) and the vertical exponential disc scale height h_z together give the surface mass density Σ of the disc via the relation:

$$\Sigma = f\sigma_z^2/Gh_z \quad (4.1)$$

where G is the gravitational constant and f is a geometric factor, known as the vertical structure constant, that depends weakly on the adopted vertical structure of the disc. The calculated surface mass density will allow us to calculate the mass-to-light ratios (M/L), which will help break the disc-halo degeneracy.

In this chapter, I discuss the observations carried out on NGC 628 to extract a two component velocity dispersion for the motion of the hot and cold disc component independently. The velocity dispersion data were combined from the two instruments discussed in Chapter 3: (1) an absorption line study of the integrated disc light using spectra from the VIRUS-W IFU instrument on the 107-inch telescope at McDonald Observatory, and (2) the velocity distribution of planetary nebulae observed using the planetary nebula spectrograph (PN.S) on the William Herschel Telescope. Section 4.2 describes the observations and data reduction for VIRUS-W, and section 4.3 summarises the same for the PN.S. Section 4.4 details the analysis involved in the extraction of a double Gaussian model from the data. Section 4.5 describes the calculation of the disc surface mass density, using the dispersion for the hot component and its implications on the rotation curve decomposition, and section 4.6 lists the conclusions from this study.

4.2 VIRUS-W Spectrograph

As discussed in Chapter 3, the VIRUS-W is an optical-fibre-based Integral Field Unit (IFU) spectrograph at the 2.7m Harlan J. Smith Telescope at the McDonald Observatory in Texas. We acquired spectra in the inner 1 scale length of NGC 628 to determine the stellar kinematics of the cold and hot thin disc components, by looking at the Mgb region of the spectra.

4.2.1 Observations

NGC 628 is a large galaxy, much larger than the field of the IFU. It was observed in October 2014. We were able to observe several fields around the galaxy with a luminosity weighted radius of about $78''$. This corresponds to about 1 scale length in the R-band (Fathi et al. 2007). We positioned the IFU along the major and minor axis as well as at intermediate position angles. Our IFU positions on the galaxy are shown in Fig. 4.1. The IFU cannot be rotated so our observations had to be made with the long axis of the IFU oriented East-West, as shown in Fig. 4.1. The distribution of fields around the galaxy allows us to separate the contributions to the line of sight velocity dispersion from the vertical and in-plane components of the stellar motions in the disc. Since the fields cover a large radial extent on the galaxy, we decided to split the data into two radial bins, at luminosity-weighted radii of $62''$ and $109''$ respectively.

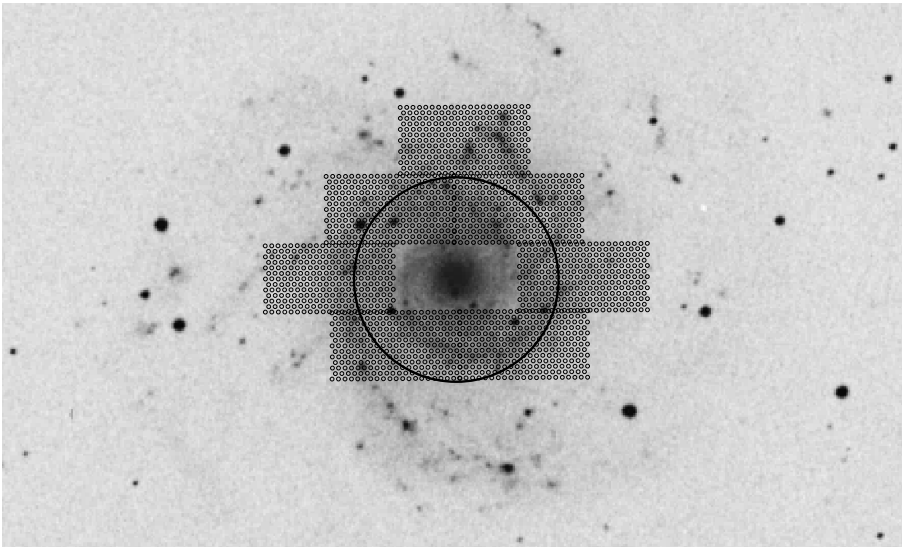


Figure 4.1: The positions of the VIRUS-W IFU fields overlaid on a DSS image of NGC 628. The position of the 267 fibres in each field are also shown. The circle at $85''$ shows where we separated our data into the inner and outer radial bin. The inner radial bin covers $25'' \leq R \leq 85''$ and the outer bin covers the region $85'' < R \leq 165''$.

The position and exposure time at each position is given in Table 4.1. Each of the galaxy exposures were preceded and followed by a sky exposure of equal time. We

repeated this sky – galaxy – sky sequence at least thrice at each field, as indicated in column 3 of Table 1. This enabled very good sky subtraction using the automated pipeline developed for VIRUS-W.

RA (J2000)	Dec (J2000)	Exposure Time (s)
1:36:49.00	+15:47:02.7	3×800
1:36:34.36	+15:47:02.1	3×800
1:36:45.19	+15:47:02.1	3×800
1:36:37.85	+15:46:06.5	3×800
1:36:45.46	+15:48:00.0	3×800
1:36:38.10	+15:47:59.1	3×800
1:36:41.16	+15:48:56.9	5×800

Table 4.1: Coordinates and exposure times for the IFU fields in NGC 628.

The details of the reduction procedure for the VIRUS-W data are explained in Chapter 3. The sky subtracted images from the reduction pipeline were combined and the spectra from each fibre in each field were summed to get a single spectrum at each of our two radial bins. This is explained in detail in section 4.4.1.

4.3 Planetary Nebula Spectrograph

The technical details of the planetary nebula spectrograph (PN.S) are discussed in-depth in Chapter 3. The PN.S has a ‘left’ and ‘right’ arm in which the light is dispersed in opposite directions. Combining these two counter-dispersed images allows the PNe to be detected and their radial velocities to be measured in a single observation. The PN.S also has an undispersed $H\alpha$ imaging arm which can help to distinguish HII regions and background $Ly\alpha$ emitters from the PNe.

The PN.S is used by the PN.S collaboration, so far mainly on early-type galaxies (Coccato et al. 2009; Cortesi et al. 2013) plus a study of PNe in M31 (Merrett et al. 2006). Arnaboldi et al. (2017) describe a new survey of nearby face-on disc galaxies, aimed at measuring the internal kinematics of these disks, and illustrate the analysis of the new PN.S data for NGC 628 (also see Chapter 3 for details).

4.3.1 Observations, Data Reduction, and Velocity Extraction

The data for NGC 628 were acquired over two nights during a 4 night observing run in September 2014. The weather during the run was excellent, with typical seeing being $\sim 1''$. We obtained 14 images centred on the centre of the galaxy, each with an exposure time of 1800s. At the redshift of NGC 628, the wavelength of the [OIII] emission is near 5018 Å.

Chapter 3 included a detailed description of the data reduction process (also see Douglas et al. 2007 and Arnaboldi et al. 2017). The automated reduction procedure debiases and flat-field-corrects the raw images from the left and right arms, using bias

frames and flats obtained during the observing run. Cosmic rays are removed using a custom-built routine in the pipeline. The wavelength calibration of the dispersed images was improved for this project by implementing a higher-order polynomial fit to the arc line calibration images taken during the observing run. After wavelength calibration, the 14 left and right arm images were stacked to create the final dispersed galaxy images.

Simultaneously with the [OIII] imaging, NGC 628 was also observed in $H\alpha$, using the $H\alpha$ narrow band filter on the undispersed $H\alpha$ arm of the PN.S. The $H\alpha$ arm and the reduction of this data are described in Arnaboldi et al. (2017).

4.3.2 Identification of Sources

We explain in Chapter 3 how we identify the 'true PNe' candidates in our galaxies (also see Arnaboldi et al. 2017). After removing extended sources, we were left with a catalogue of 716 unresolved [OIII] sources. From the measured positions of these sources on the left and right images, astrometric positions and LOS velocities were derived simultaneously.

We converted our instrumental magnitudes to the m_{5007} magnitude scale used by Herrmann & Ciardullo (2009b), using our spectrophotometric calibration. This allows us to directly compare our results to the values in Herrmann & Ciardullo (2009b). From here on, we shall only be using these m_{5007} values. The bright luminosity cut-off for PNe in this galaxy is expected to be $m_{5007} = 24.73$.

Our sample of 716 identified sources is still a mixture of HII regions and PNe, since both can have strong unresolved [OIII] emissions. In the paper, Arnaboldi et al. (2017), we detail how we separated the spatially unresolved HII regions from PNe in the disc of NGC 628 using an [OIII]/ $H\alpha$ color-magnitude cut that accounts for the apparent [OIII] magnitude of the bright cut-off in the PNLF and the large [OIII]/ $H\alpha$ emission line ratio of bright PNe (see Fig. 3.7 in Chapter 3).

The line-of-sight velocity distributions of the HII regions and the PNe have different second moments (σ_{LOS}) in different radial bins. The σ_{LOS} for the PNe correlates with m_{5007} . There is a kinematically cold population near the PNLF bright cut off, and then the velocity dispersion increases towards fainter magnitudes. This correlation is reminiscent of the age-magnitude-(vertical velocity dispersion) relation of the K-giant stars in the solar neighbourhood as shown in Chapter 2.

Another possible source of contaminants in the emission line sample are historical supernovae. According to the IAU Central Bureau for Astronomical Telegrams (CBAT) List of Supernovae website (<http://www.cbat.eps.harvard.edu/lists/Supernovae.html>), there are three known historical supernovae in NGC 628. None of these objects made it into our PNe sample. An [OIII] emission line source was found at a distance of $1.6''$ from SN 2002ap. However, on applying our colour-magnitude cut, this object was classified as an HII region. We, therefore, conclude that these contaminants are removed from our PNe sample by the colour-magnitude cut as well.

Fig. 4.2 shows the luminosity function, including all 716 sources, and indicates the position of the bright luminosity cut-off for the PNe. The colour-magnitude cut

on our 716 emission objects left us with about 400 objects. The LOS velocities for this sample are then used to calculate the velocity dispersions for the hot and cold PNe components.

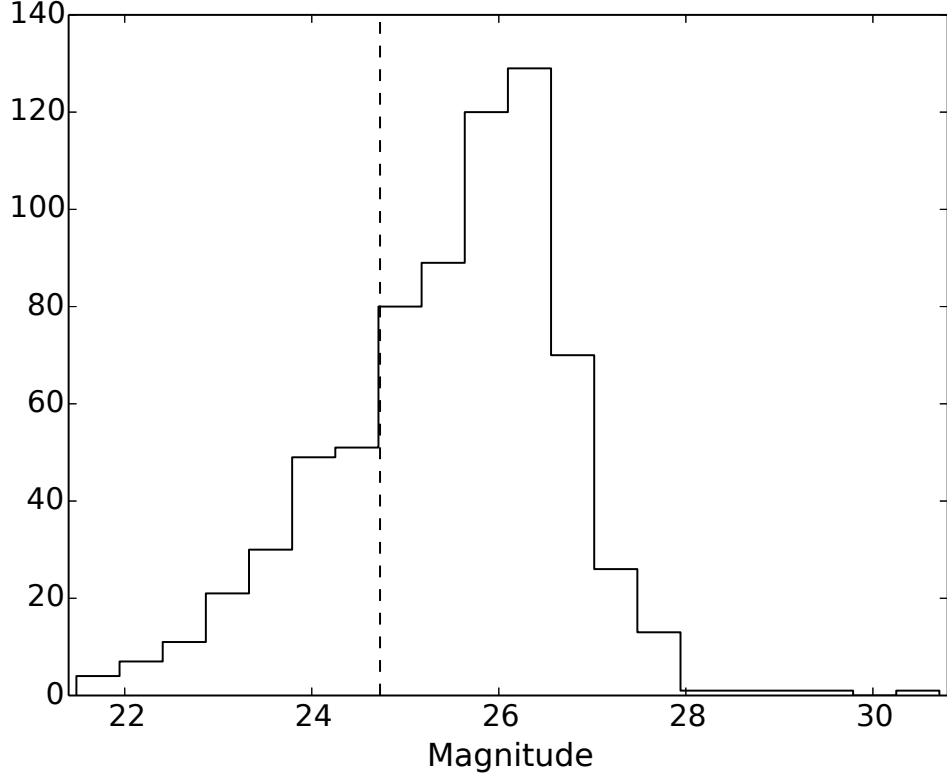


Figure 4.2: The luminosity function for all spatially unresolved [OIII] emitters identified in the combined left and right images of the PN.S. The dashed line shows the expected bright luminosity cut-off for PNe. We include only objects fainter than this value in our analysis. Objects brighter than the cut-off are mostly obvious bright HII regions.

4.3.3 Velocity errors

Space and wavelength information are closely related in an imaging spectrograph like the PN.S (see section 4.3.2). The left and right PN.S images are registered on the best quality image, which had the best seeing etc, so there is some correlation between the frames. In order to get an empirical estimate of the radial velocity measuring errors associated with each PN, we divided our 14 left and right images into two sets and then independently identified the unresolved [OIII] sources in each set. We had to split our sample into a set of 8 images and 7 images, since the 'reference image' used to stack the other images was common to both sets. We assume the radial velocity errors depend only on the total counts, not on the number of frames and that the velocity error of a single measurement at each count level, for all 14 frames, is the (rms of the difference between two velocity measurements at

that count level)/ $\sqrt{2}$, if there was no correlation between different images. However, since we had one image in common between the two sets, we carried out monte carlo simulations on the two image sets and the combined final image and found that the typical radial velocity error of a single measurement at each magnitude in the final image is $(1/1.805)$ times the rms velocity difference between the two image sets at the same magnitude. Fig. 4.3 shows the error expected for a single measurement from the whole set of 14 images, as a function of the m_{5007} magnitude. Objects used in the subsequent analysis are those to the right of the vertical dashed line, which marks our bright cut-off. Most of these objects have estimated radial velocity errors between about 4 and 9 km s^{-1} .

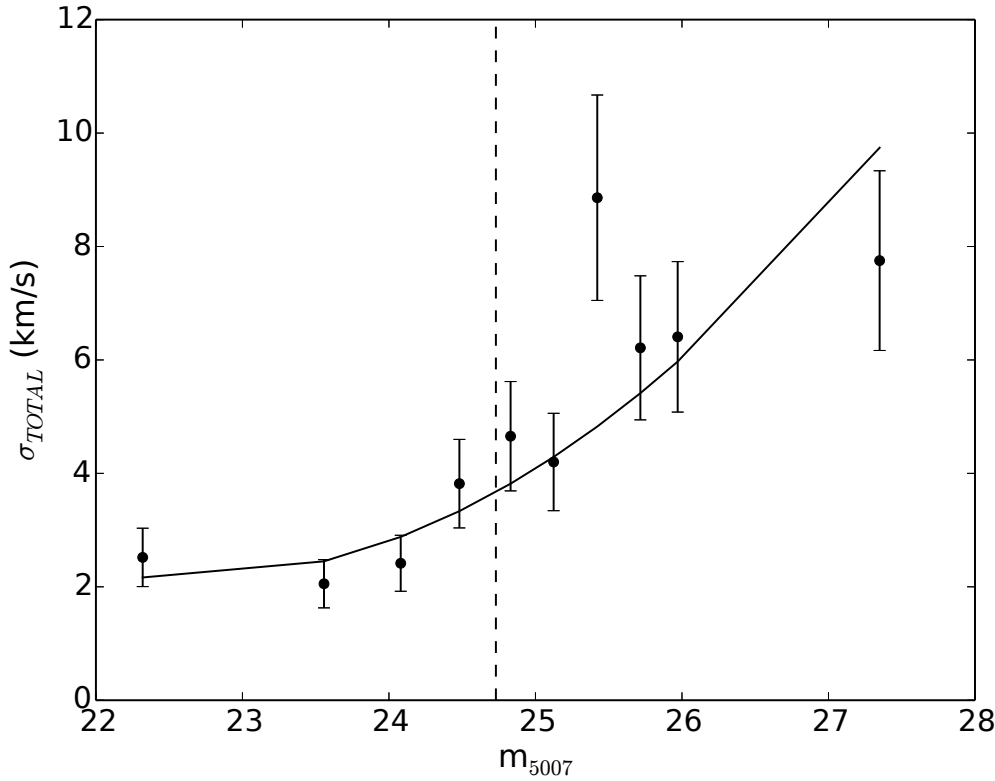


Figure 4.3: The measuring error for our sample of objects as a function of apparent magnitude. The magnitude system is the same as in Herrmann & Ciardullo (2009b). The dashed line shows the bright luminosity cut-off for this galaxy. Only the objects fainter than this magnitude were used in our analysis. The solid curve is the best fit to the data.

4.4 Extracting Velocity Dispersions of the Hot and Cold Components

In our analysis, we adopted some parameters for NGC 628 from the literature, using the same sources as Herrmann & Ciardullo (2009b) and Bershadsky et al. (2010a).

These parameters are listed in Table 4.2. We adopt the same parameters as Herrmann & Ciardullo (2009b) where possible to minimise difference when comparing final outcome.

Parameters	Value	Source
Scale length (R - band)	76.0''	Fathi et al. (2007)
Distance	8.6 ± 0.3 Mpc	Herrmann et al. (2008)

Table 4.2: The parameters for NGC 628 adopted from the literature and used in our analysis.

Apart from these adopted values, based on kinematic fits to the THINGS HI data (Walter et al. 2008) for this galaxy, we determined the inclination of the galaxy to be 8° . We will be using these values in our analysis from here on.

4.4.1 Stellar Absorption Spectra

4.4.1.1 Removing Galactic Rotation

For the VIRUS-W data, the automated pipeline 'CURE' returns a two dimensional FITS image, where each row represents a fibre spectrum and the x-axis is the wavelength dimension. Our goal is to measure the line of sight velocity dispersion (σ_{LOS}) without including the effects of galactic rotation across the field of the IFU. One option for removing galactic rotation would be to model the rotation field over the IFU using the observed rotation curve. Alternatively, we could use the local observed HI velocity at the position of each of the IFU fibres, and we have chosen this option. We used the 21 cm HI data from the THINGS survey (Walter et al. 2008). The spectrum from each fibre is shifted in velocity by the local HI velocity. Although this procedure removes the galactic rotation and any large scale streaming motions across the field of the IFU, it will however introduce an additional small component of velocity dispersion to the apparent stellar velocity dispersion. This is because the motion of the gas is not purely circular and we will need to correct for its effect on the derived stellar dispersion.

Initially, we made a double Gaussian analysis to derive the velocity dispersion for the hot and cold components of the disc. To get sufficient SNR for this double Gaussian analysis, we sum up all the shifted spectra (one from each fibre) over the IFU field, to get a single spectrum (at each radial bin). IFU fibres that fell on stars in the field are excluded from the sum.

We then attempted to carry out a triple Gaussian fit to the data, to check if we have any contribution from the thick disc. However, we could not get a third component in our fit when the data were divided into two radial bins. The degeneracy between the hot thin disc and the thick disc component led to errors that were unacceptably large. We were able to get a third component with a dispersion consistent with a thick disc component if we only considered one radial bin and summed up the data from all the fibres. However, this third component may just be an artefact of the gradient of the velocity dispersion, since we are summing up the

data over such a large radial extent. The information criterion that we used to judge the best model (see section 4.1.2) also rejects the three component fit. Therefore, we conclude that there is no significant thick disc contribution present in our data.

The final summed spectra used in our analysis have an SNR of 79 and 62 per wavelength pixel for the spectrum from the inner and outer radial bins respectively (each wavelength pixel is $\sim 0.19 \text{ \AA}$). These SNR values are empirical estimates obtained by taking into consideration the contribution of the galaxy and sky shot noise and the readout noise (2.55 e^-) of the detector. The VIRUS-W instrument has wavelength-dependent resolution, offering the highest resolution $R \sim 9000$, around the Mgb region ($\lambda \sim 5160 \text{ \AA}$). Therefore, we only used the region between wavelengths of about $5050 - 5300 \text{ \AA}$ in our analysis, since it has the highest resolution and avoids the emission lines at lower wavelengths. The [NI] doublet emission lines from the interstellar medium of the galaxy can be seen at $\sim 5200 \text{ \AA}$ (see Fig. 4.4). These are not residual sky lines: they appear at the redshift of the galaxy.

4.4.1.2 Measuring the LOSVD

We used the penalized pixel-fitting code pPXF developed by Cappellari & Emsellem (2004) to get the mean velocity and velocity dispersion of the two components. This code uses a list of stellar templates to directly fit the spectrum in pixel space to recover the line of sight velocity distribution (LOSVD). pPXF can fit up to six higher moments to describe the LOSVD. It has options to fit either 1 or 2 LOSVD to the given spectrum, each with up to 6 moments. We used stars of different spectral types observed with VIRUS-W as our list of stellar templates. This avoids any problems of resolution mismatch between the stellar templates and the galaxy spectrum. pPXF then finds a best-fit spectrum to the galaxy spectrum, which is a linear combination of different stellar templates. We assume the two components of the LOSVD to be Gaussian for this nearly face-on galaxy, and therefore retrieved only the first and second moment parameters from pPXF.

As explained in section 4.1.1, we did a double Gaussian fit to the data, fitting for two moments for each component. In this case, pPXF returns the velocity and the line-of-sight (LOS) dispersions for the two component and for the single component fit. Adding more parameters to the model invariably improves the fit to the data. We therefore need to quantitatively decide whether the 2 Gaussian or single Gaussian model is a more appropriate fit to the data. To do this, we used the Bayesian Information Criterion (BIC, Schwarz 1978), which is calculated using the relation:

$$\text{BIC} = -2 \cdot \ln \hat{L} + k \cdot \ln(n), \quad (4.2)$$

where $\hat{L}$ is the maximized value of the likelihood function of the model, n is the number of data points or equivalently the sample size and k is the number of free parameters to be estimated. Under the assumption that the model errors are independent and are Gaussian, Eqn. 4.2 becomes:

$$\text{BIC} = n \cdot \ln(RSS/n) + k \cdot \ln(n) \quad (4.3)$$

where RSS is the residual sum of squares.

The BIC penalises the model with the larger number of fitted parameters and, between 2 models, the model with the lower BIC value is preferred. The values of the BIC for our VIRUS-W spectra are tabulated in Table 4.3. Since the model with the lower value of BIC is preferred, the two component fit is preferred over the single component fits in both of the radial bins.

pPXF found an excellent fit to our spectrum, as shown in Fig. 4.4. It returns the adopted spectra of the individual components, and the 2 spectra that it returns are consistent with the spectra of red giants. The mean contributions of the cold and hot disc components to the total light are 36% and 64% respectively.

As mentioned above, since we used the THINGS HI data to remove rotation across the fields, we need to correct these two dispersion values for the contribution from the HI velocity dispersion. This correction was determined by fitting a plane function $V = ax + by + c$ to the HI velocities at the (x, y) location of the individual VIRUS-W fibres at each IFU pointing. The rms scatter of the HI velocities about this plane is 2.5 km s^{-1} . We note that this is the rms scatter of the mean HI velocities from fibre to fibre, which is not the same as the HI second moment. Correcting for this scatter changes the observed dispersions by only a very small amount. Table 4.3 shows our results after subtracting this value quadratically from the pPXF results. The errors given in Table 4.3 are the 1σ errors obtained from monte carlo simulations. This was done by running 1000 iterations where, in each iteration, random Gaussian noise appropriate to the observed SN of the IFU data was added to the best fit spectrum originally returned by pPXF. pPXF was run again on the new spectrum produced in each iteration. The errors are the standard deviations of the distribution of values obtained over 1000 iterations.

Mean Radius (arcsec)	2 component Model				1 Component Model		
	$\sigma_{z,cold}$ (km s^{-1})	$\sigma_{z,hot}$ (km s^{-1})	χ^2_{red}	BIC	σ_z (km s^{-1})	χ^2_{red}	BIC
62	16.5 ± 3.7	55.4 ± 6.5	0.95	17923	31.6 ± 1.1	1.04	18107
109	14.9 ± 3.8	50.9 ± 9.0	1.11	19021	24.9 ± 1.2	1.15	19064

Table 4.3: The single and double Gaussian fit from pPXF. For each component, the Table gives the vertical velocity dispersion σ_z for each of the components; see section 4.1.3. Dispersions have been corrected for the contribution from the HI velocity dispersion. An estimate of the reduced χ^2 and the Bayesian Information Criterion parameter BIC defined in Eqn. (3) is also given.

4.4.1.3 Extracting the Vertical Velocity Dispersion

The vertical component of the stellar velocity dispersion σ_z was calculated from the line of sight component σ_{LOS} by first calculating the azimuthal angle (θ) to each fibre. The angle θ is measured in the plane of the galaxy, from the line of nodes. Then the LOS dispersion is given by:

$$\sigma_{LOS}^2 = \sigma_\theta^2 \cos^2 \theta \cdot \sin^2 i + \sigma_R^2 \sin^2 \theta \cdot \sin^2 i + \sigma_z^2 \cos^2 i + \sigma_{meas}^2 \quad (4.4)$$

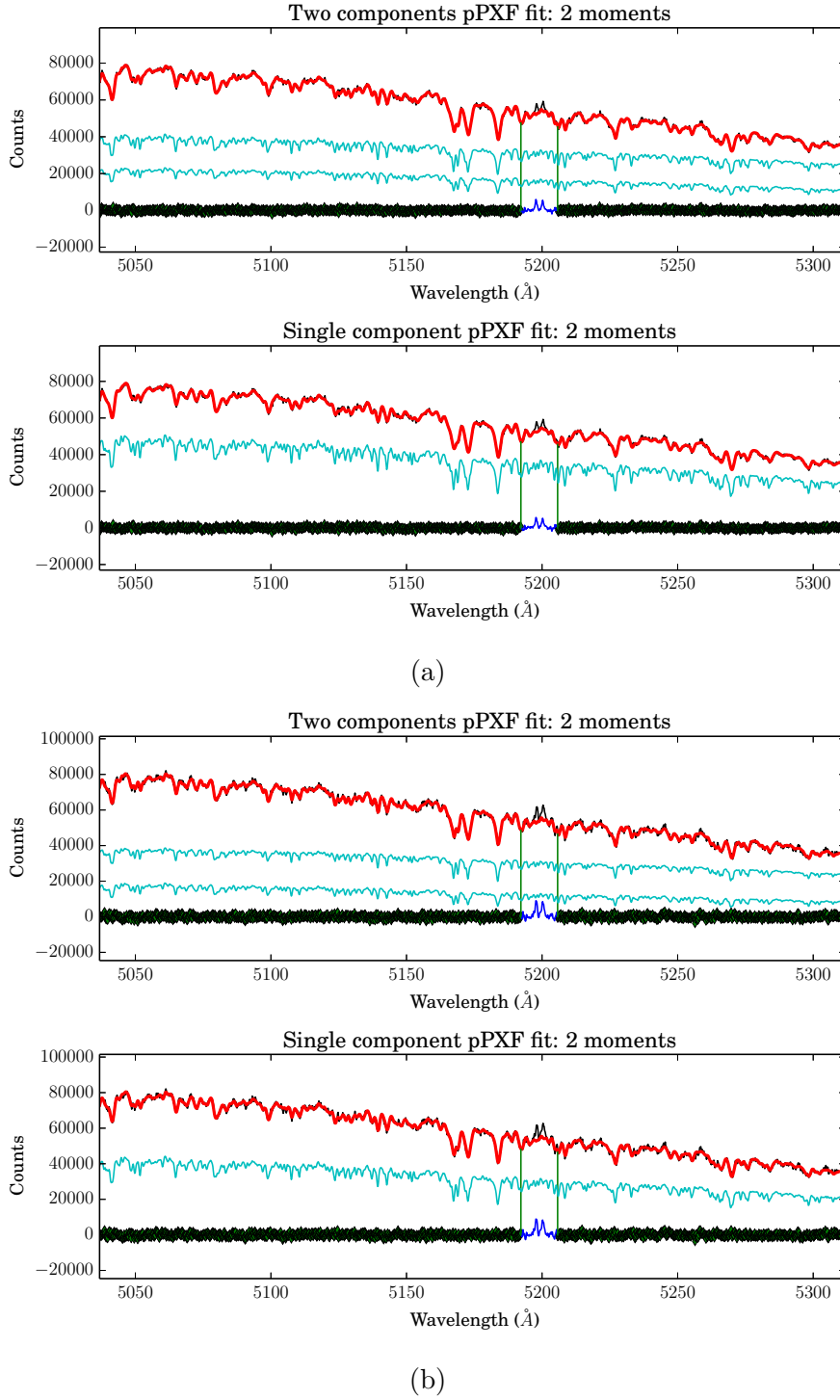


Figure 4.4: The pPXF fit results in (a) the inner radial bin at a luminosity weighted distance of $62''$ and (b) the outer bin at a luminosity weighted distance of $109''$. The upper panel shows the 2 component fit to the data whereas the lower panel shows a single component fit. Only the high resolution Mgb region of the spectrum was used for the fit. The galaxy spectrum is in black and the best fit from pPXF is in red. The cyan spectra are the two and one component spectra that pPXF found. The cyan spectra have been shifted vertically so as to be clearly visible. The residuals are shown in dark green. The [NI] doublet emission lines from the galaxy at ~ 5200 Å have been omitted from the fit.

where σ_R , σ_θ and σ_z are the three components of the dispersion in the radial, azimuthal and vertical direction, σ_{meas} are the measurement errors on the velocity and i is the inclination of the galaxy ($i = 0$ is face-on). This galaxy is too face-on to solve independently for the in-plane velocity dispersion components. We wish to remove the small contribution that the planar components make to the LOS distribution, so we adopt $\sigma_R = \sigma_\theta$ for $R < 80''$ where we take the rotation curve to be close to solid body. This is a fair assumption, based on an examination of the THINGS HI velocities along the galaxy's kinematic major axis. We also adopt the σ_R/σ_z ratio to be 1.7, which is consistent with the value used by Bershadsky et al. (2010b) and the value found in the solar neighbourhood. Eqn. 4 then gives σ_z in terms of σ_{LOS} . Since NGC 628 is almost face-on, the σ_{LOS} and σ_z values are almost the same.

Our choice to remove the rotation and streaming across the IFU fields by using the local HI velocities introduced a small additional broadening of the LOS velocity distribution, as described above. This small broadening ($\sim 2.5 \text{ km s}^{-1}$) was quadratically subtracted from the dispersion values returned by pPXF. Our results for the stellar σ_z values are presented in Table 4.3. The errors are the 1σ errors from monte carlo simulations (as explained in section 4.1.2).

4.4.2 Planetary Nebulae

4.4.2.1 Removing Galactic Rotation

As in the analysis of the IFU integrated light absorption spectra, we again need to remove the effects of galactic rotation from the PNe velocity field. We used the THINGS HI data as before, and obtained the HI velocity at the position of all our PNe from the THINGS first moment data. There appeared to be a small systematic offset $\sim 15 \text{ km s}^{-1}$ between our PNe velocities and the THINGS HI data. We calculated this offset by cross-correlating the two data sets and determining the velocity of the correlation peak. This offset was then subtracted from the PNe velocities. The local HI velocities were then subtracted from these offset-corrected PNe velocities.

These velocities, corrected for the offset and with the galactic rotation removed are henceforth denoted v_{LOS} . They are the velocities that are used in our analysis to calculate the velocity dispersions. As for the IFU data (section 4.1.3), the radius and azimuthal angle (θ) of the PNe in the plane of the galaxy were calculated, and the v_{LOS} data were then radially binned into 3 bins, each with about 130 PNe. As explained in section 3.3, we applied a colour-magnitude cut using the [OIII] and H α magnitudes, to separate out the contamination from likely HII regions. Fig. 4.5 shows the v_{LOS} vs θ plots in each radial bin before and after the HI velocities were subtracted. Very few PNe were identified in the rising part of the rotation curve i.e at $R < 80''$. Most of the identified unresolved objects ended up being classified as HII regions. Since the rising part of the rotation curve is considered to be a solid body with a different set of assumptions, they cannot be clubbed together with the PNe at $R > 80''$. We, therefore, omitted these PNe and only included the objects with radii $> 80''$ in our analysis.

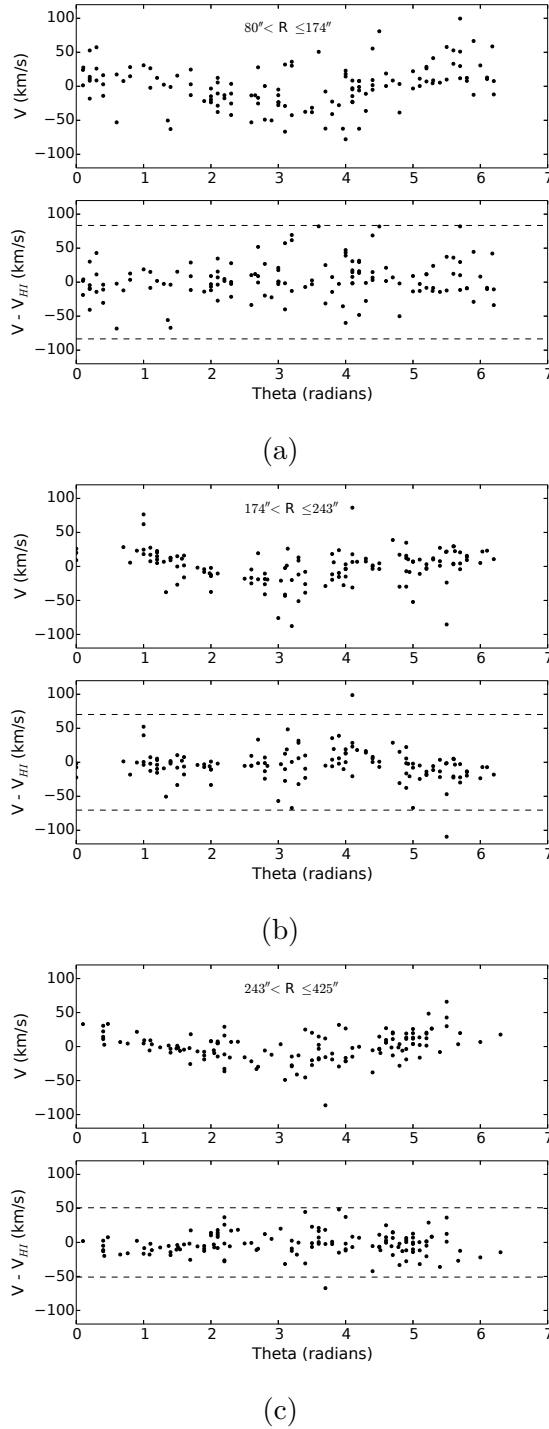


Figure 4.5: Velocity vs azimuthal angle plots in 3 radial bins, each with about 130 PNe. The angle θ is in the plane of the galaxy and measured from the line of nodes. The top panels show the velocity before correcting for galactic rotation and the bottom panels show the velocities after the THINGS HI velocities have been subtracted off. A few objects with velocity $> 3\sigma$ were removed from the sample. The objects within the dashed lines are the ones that were included in our sample for analysis. Each panel shows a cold population of spatially unresolved emission line objects, plus a hotter population whose velocity dispersion appears to decrease with galactic radius.

4.4.2.2 Extracting the LOSVD

In each radial bin, we remove a few 3σ outliers, consistent with the analysis by Herrmann & Ciardullo (2009b), who clipped their sample of PNe to remove high-velocity contaminants from their sample. These outliers could be halo PNe or thick disc objects, and should be removed from our sample. Only a small number of objects in each radial bin have velocities $> 3\sigma$. A maximum likelihood estimator (MLE) routine written in python was then used to calculate the LOS velocity dispersions and the subsequent σ_z in each radial bin.

The first iteration in this routine estimates σ_{LOS} for the two components. The routine maximises the likelihood for the two-component probability distribution function given by:

$$P(\mu_1, \sigma_1, \mu_2, \sigma_2) = \frac{1}{\sqrt{2\pi}} \left[\frac{N}{\sigma_1} \exp\left(-\frac{(v_{LOS} - \mu_1)^2}{2\sigma_1^2}\right) + \frac{1 - N}{\sigma_2} \exp\left(-\frac{(v_{LOS} - \mu_2)^2}{2\sigma_2^2}\right) \right] \quad (4.5)$$

In Eqn. 4.5, μ_1 and μ_2 are the mean LOS velocities and σ_1 and σ_2 are the LOS dispersions of the cold and hot component respectively. N is the fraction of the cold tracers in the data.

4.4.2.3 Extracting the Vertical Velocity Dispersion

In order to calculate the surface mass density using Eqn. 4.1, we need the vertical velocity dispersion of the hot component. For NGC 628, which is a near face-on system, the σ_z value will be very close to the σ_{LOS} values. To determine this value, we again use an MLE method. Two parameters are passed to the function in this stage: σ_{z1} and σ_{z2} which are the vertical velocity dispersions of the cold and hot components respectively. The σ_{LOS} values obtained using the method described above are passed to the routine as initial guesses, since the σ_z will be very close to the value of σ_{LOS} for this galaxy. We assume $f = \sigma_R/\sigma_z = 1.7$ (Bershady et al. 2010b) and use inclination $i = 8^\circ$ as explained earlier in section 4. The PN.S data are all at radii $> 80''$ where the rotation curve is flat, and we use the epicyclic approximation: $\sigma_R = \sqrt{2}\sigma_\theta$, where σ_R and σ_θ are the in-plane dispersions in the radial and azimuthal directions. Now there is only one unknown σ_z , which we need to calculate.

Once the initial guesses are passed to the routine, it calculates the expected σ_{LOS} for the hot and cold component at each azimuthal angle (θ) using the relation:

$$\begin{aligned} \sigma_{LOS1}^2 &= \frac{\sigma_{z1}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 \cos^2 i \\ \sigma_{LOS2}^2 &= \frac{\sigma_{z2}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 \cos^2 i \end{aligned}$$

The subscript 1 and 2 refers to the components of the cold and hot populations respectively. The code then proceeds to calculate the probability of a particular

v_{LOS} to be present at that azimuthal angle via the analytic equation:

$$P = \frac{N}{\sigma_{LOS1}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_1 \cos \theta \cdot \sin i)^2}{2\sigma_{LOS1}^2}\right) + \frac{1-N}{\sigma_{LOS2}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_2 \cos \theta \cdot \sin i)^2}{2\sigma_{LOS2}^2}\right) \quad (4.6)$$

In Eqn. 4.6, N is the value of the fraction of the cold population returned by the routine that calculated σ_{LOS} described earlier. μ_1 and μ_2 were fixed at 0 km s⁻¹ in our analysis. We tried to leave the two means as parameters to be estimated by the code, but since NGC 628 has such a low inclination, these parameters would not converge. It is difficult to get an estimate of the asymmetric drift in such a face-on galaxy. So we assumed that the mean of the cold PNe were at the same velocity as the gas, at 0 km s⁻¹. We did try changing the mean of the hot PNe up to an asymmetric drift of 5 km s⁻¹ but this did not cause any significant changes in the σ_z values. Eqn. 4.6 is then maximised to return the best fit values for σ_z for the hot and cold population of PNe. The 1σ errors are calculated similar to the method used in the analysis of the VIRUS-W data. We carried out our monte carlo error estimation by using the double Gaussian distribution found by our MLE code, to pull out about 130 random velocities (i.e same number of objects as in each of our bins). We then used this new sample to calculate the σ_z of the hot and cold component using our MLE routines. This whole process was repeated 1000 times, recording the dispersions returned in each iteration. The 1σ error is then the standard deviation of the distribution of the dispersions returned from these 1000 iterations.

The parameters returned from the MLE routine that does the double Gaussian decomposition is given in Table 4.4. Fig. 4.6 shows the σ_z vs radius for NGC 628. The data points at a radius of 62'' and 109'' come from the VIRUS-W spectra in the inner field. Similar to the VIRUS-W analysis, we need to correct the dispersions for the PNe, because of the scatter in the the local THINGS HI velocity which we used to remove the galactic rotation. This correction was done as for the IFU data analysis by quadratically subtracting this small dispersion (~ 2.5 km s⁻¹) from the values of the dispersions returned by the MLE routine. We also need to correct the measured dispersions for the measuring errors of the individual PNe, as shown in Fig. 4.3. The rms measuring error in each radial bin is about 6 km s⁻¹. The formal variance of the corrected cold dispersion value at a radius of 208'' is negative. Hence we show its 90% confidence upper limit in Fig. 4.6 and Table 4.4.

The PNe population selected by the colour-magnitude cut (see section 3.2) includes a population of kinematically cold sources. If this cold component had not been present, Herrmann & Ciardullo (2009b) would probably have measured larger velocity dispersions and higher surface mass densities. From the analysis of the cold and hot PNe population, as well as the identified HII regions (Arnaboldi et al. 2017), the PNe near the bright cut-off of the PNLF are kinematically colder than the HII regions at the same m_{5007} magnitude, with $\sigma_{HII}/\sigma_{PNe} \sim 2$. Thus, these cold bright PNe are unlikely to be contaminant HII regions, since the LOS velocity distributions

of the two classes of objects are so different. Work done by Miller Bertolami (2016) suggests that PNe from massive progenitors evolve very fast. Thus massive progenitors, i.e. young massive stars, produce bright PNe that are still kinematically very cold.

4.5 Results

Fig. 4.6 shows the results obtained from the integrated light VIRUS-W data (points at $R = 62''$ and $109''$) and the planetary nebulae from the PN.S data (3 outer points) in each radial bin. At each radius, we show our one component dispersion, and then the hot and cold thin disc dispersion from our double Gaussian fit. The dispersions obtained from Herrmann & Ciardullo (2009b) are also plotted for comparison.

As mentioned in the previous section, the dispersion values that we obtained from our analysis have been corrected for the small local HI dispersion, which was introduced when we used the HI data to remove galactic rotation, and for the measuring errors for the velocities of individual PNe. The corrections to our hot-component dispersions, which are the goal of the paper, are small.

The solid curve in Fig. 4.6 is the expected exponential curve for a simple old radially exponential disc, with a scale length twice the observed photometric scale length of the disc ($h_R = 76.0'' = 3.17$ kpc in the R-band, see Table 4.2). Fitting this curve to the data, we find that the central vertical dispersion for the hot component is $\sigma_{z,0} = 87.6 \pm 5.2$ km s⁻¹.

Fig. 4.6 shows in red the PNe velocity dispersions derived for this galaxy by Herrmann & Ciardullo (2009b). Our one-component PNe velocity dispersions agree well with their results. We note that the difference between the one component dispersions and our hot component dispersions decreases with radius and is quite small for our outermost radial bin. This is consistent with the BIC values shown for the outer radial bin, which does not favour the two component model in the outer bin. The one component value for the last bin is also closer to our exponential disc curve than the two component value.

Mean Radius (arcsec)	2 component Model			1 Component Model	
	$\sigma_{z,cold}$ (km s ⁻¹)	$\sigma_{z,hot}$ (km s ⁻¹)	BIC	σ_z (km s ⁻¹)	BIC
132	4.6 ± 2.6	33.8 ± 3.8	1269	26.5 ± 1.7	1272
208	$\leq 6.7 \pm 1.9$	22.6 ± 2.5	1160	18.6 ± 1.2	1164
293	6.2 ± 3.6	17.5 ± 3.6	1124	14.5 ± 1.0	1118

Table 4.4: The σ_z values calculated from the PN.S data. We give the 90% confidence upper limit for the cold dispersion in the second radial bin (see section 4.2.3 for details). The lower BIC values of the two component fit (except in the outermost radial bin) make it the preferred model over the one component model.

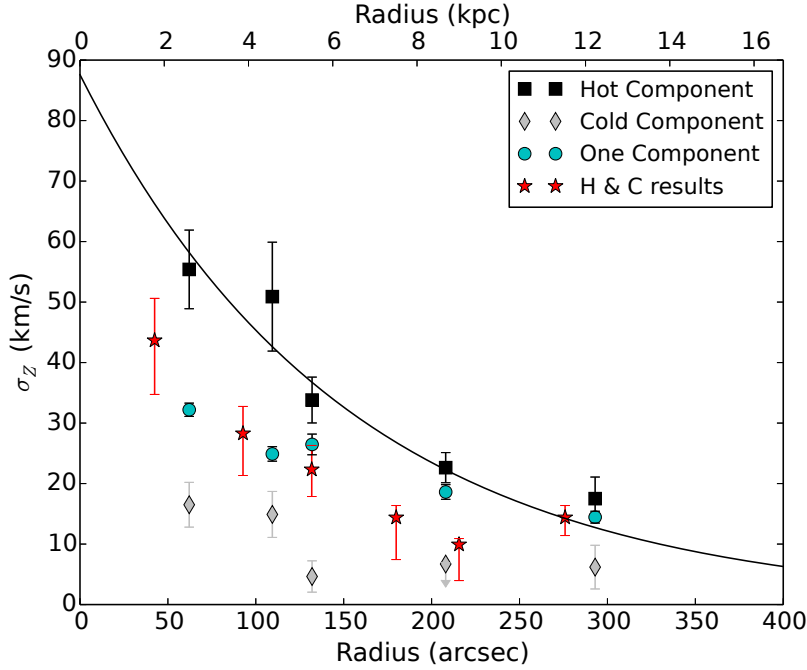


Figure 4.6: The σ_z per radial bin in NGC 628. The black and grey markers indicate the hot and cold velocity dispersions respectively from our two component fits. The cyan markers are our single-component values, and the points in red are the Herrmann & Ciardullo (2009b) PNe data. The data points at $R = 62''$ and $109''$ were obtained for integrated light spectra from VIRUS-W and the outer data points are for PNe from PN.S. The solid line denotes an exponential with twice the galaxy’s R-band scale length ($h_R = 76'' = 3.17$ kpc, based on literature value), fit to the hot component. Our data have been corrected for the HI velocity dispersion and PNe velocity errors (see section 4.2.3 for more details). The errors bars are the 1σ errors obtained from monte carlo simulations.

4.5.1 Vertical Structure of the Disc

Having calculated the σ_z in each radial bin in NGC 628, we can now proceed to calculate the surface mass density Σ of the disc using Eqn. 4.1. We need to adopt values for the old disc scale height h_z and the vertical structure constant f .

Herrmann & Ciardullo (2009b) chose to model their disc using an intermediate vertical distribution, where the vertical density of the disc $\rho(z) \propto \text{sech}(z/h_z)$. They took the value of the geometric factor f in Eqn. 4.1 to be equal to $1/1.7051\pi$. We note that the values of f for the Herrmann & Ciardullo (2009b) disc and for the isothermal disc and for the vertically exponential disc differ by only a few percent. The parameter h_z is not directly observable in near-face-on systems. It needs to be estimated from other observables of the galaxy such as disc scale length h_R , disc surface brightness and circular velocity, using correlations established in previous works. Several studies have found $h_R/h_z \sim 10$ for large late-type spirals such as NGC 628 (e.g. de Grijs & van der Kruit 1996, Kregel et al. 2002, Yoachim & Dalcanton 2006). Studies such as Kregel et al. (2002) have explored the behaviour of h_R/h_z versus Hubble type. Both works find that, though later-type spirals generally have

larger h_z values than earlier type objects, they also have larger values of h_R/h_z . The study by Bizyaev & Mitronova (2002) examined the dependence of h_R/h_z on K-band central surface brightness K_0 (in mag/arcsec²) and found that $h_R/h_z = (0.65 - 0.0295K_0)^{-1}$. Herrmann & Ciardullo (2009b) use these results to constraint the h_z value for NGC 628 to be in the range 300 - 500 pc (see their Table 2). They also use the Toomre criterion to further constraint their dispersion and scale height values. They adopt a scale height of $h_z = 400 \pm 80$ pc, to derive a central surface mass density of $\Sigma(0) = 305^{+65}_{-48}(h_z/400 \text{ pc})^{-1} \text{M}_\odot \text{pc}^{-2}$.

We adopt an isothermal model rather than the intermediate model adopted by Herrmann & Ciardullo (2009b) i.e the vertical density of the disc $\rho(z) \propto \exp(-z/h_z)$. Several works, such as those by Wainscoat et al. (1989), have shown the vertical density distribution of spiral galaxies to follow an exponential profile. We are modelling the disc of this galaxy as the sum of the hot and cold components. The sum of these two components should then have an exponential profile. This is readily achievable with a pair of isothermal distributions. The difference between the two distributions is only significant at low disc heights. For our analysis, we adopt the value of $f = 1/2\pi$ corresponding to a self-gravitating isothermal disc. However, we note that the total density $\rho(z)$ of the disc may have significant contributions from the surface mass densities of the cold population of gas and young stars, which is not included in the description of the vertical equilibrium of the disc in Eqn. 4.1. At this stage, for ease of comparison, we will follow previous authors and neglect the gravitational field of the cold layer. In Appendix B, we quantitatively demonstrate the effect on the derived surface density of the hot disc from including the gravitational potential of the cold layer.

If we were to use the same f value and scale height as Herrmann & Ciardullo (2009b) and adopting the dispersion of the hot component, our central surface mass density would be $\Sigma(0) = 832 \pm 194 \text{ M}_\odot \text{pc}^{-2}$. This is a factor of $2.7\times$ larger than the value calculated by Herrmann & Ciardullo (2009b). If we adopt the same scale height as Herrmann & Ciardullo (2009b) but use our σ_z and f values for the hot component of the disc, the central surface mass density is $\Sigma(0) = 710 \pm 165 \text{ M}_\odot \text{pc}^{-2}$. Using surface brightness profiles from Möllenhoff (2004) and the foreground extinction correction from Schlafly & Finkbeiner (2011), we calculate the central M/L in the R band to be 2.9 ± 0.7 , about $2.1\times$ larger than the value of 1.4 ± 0.3 obtained by Herrmann & Ciardullo (2009b).

4.5.2 Estimating Disc Scale Height

It is possible to estimate the scale height of disc galaxies from the correlation of scale height and circular velocity (Yoachim & Dalcanton 2006). Since NGC 628 is so nearly face-on, it is difficult to measure its circular velocity V_c directly. We attempted to make an independent estimate of the scale height, using the absolute magnitude of NGC 628 to estimate its circular velocity and hence the scale height. The apparent B magnitude of $m_B = 9.35$ (Walter et al. 2008), and the adopted distance $D = 8.6 \pm 0.3$ Mpc (Herrmann et al. 2008) give an absolute magnitude $M_B = -20.30 \pm 0.08$.

Sakai et al. (2000) provide a relation between the absolute magnitude and the HI line widths W_{20}^c corrected for inclination angle and redshift, based on cepheid distances:

$$M_B = -(7.97 \pm 0.72)(\log W_{20}^c - 2.5) - (19.8 \pm 0.11) \quad (4.7)$$

If we take $V_c = W_{20}^c/2$ and the above estimate of absolute magnitude, then our calculated $V_c = 182.5 \pm 7.4 \text{ km s}^{-1}$. Previous studies have explored the correlation between scale height h_z of the thin disc and circular velocities of edge-on galaxies (see Fig. 9 in Yoachim & Dalcanton 2006) and found that $h_z = 305(V_c(\text{km s}^{-1})/100)^{0.9}$ pc. This study took the vertical density distribution to be isothermal. We use this relation to estimate $h_z = 524 \pm 19$ pc, which is much higher than the scale height of the MW ~ 300 pc. Yoachim & Dalcanton (2006) mention that for massive galaxies with large circular velocities ($V_c > 170 \text{ km s}^{-1}$), their derived value for the scale height of the thin disc is larger than that for the MW. This could be because these galaxies have more prominent dust lanes, which may substantially obscure our view of the thin disc and lead to an overestimate of its scale height.

We then attempted to derive the scale height from Comerón et al. (2011) who studied edge-on galaxies using an average of the 3.6 and 4.5 micron Spitzer images. From their relation between thin disc scale height and circular velocity, we calculated the h_z for NGC 628 to be about 249 pc. It seems clear that the scale heights based on existing data are uncertain. Deep K-band imaging could reduce the uncertainties, but are currently lacking in the literature.

Bershady et al. (2010b) fit the Kregel et al. (2002) data and find the relation: $\log(h_R/h_z) = 0.367 \log(h_R/\text{kpc}) + 0.708 \pm 0.095$. Using this relation for NGC 628, we get $h_z = 407 \pm 89$ pc.

Due to the uncertainty in the scale height of NGC 628, we decided to use the same value as Herrmann & Ciardullo (2009b). This value is intermediate relative to the two extreme values we get from Yoachim & Dalcanton (2006) and Comerón et al. (2011). We adopt $h_z = 400$ pc (uncertainty estimated at $\sim 20\%$). This value agrees well with the value we get using the relation adopted by Bershady et al. (2010b).

4.5.3 Stellar Surface Mass Density: isothermal model excluding the gravity of the cold component

Using Eqn. 4.1 and $f = 1/2\pi$ (isothermal model), we calculated the surface mass density in each of our radial bins. The results are tabulated in Table 4.5. Using the BVRI surface brightness profiles from Möllenhoff (2004) and the $3.6\mu\text{m}$ brightness profile from Salo et al. (2015), along with the foreground extinction correction from Schlafly & Finkbeiner (2011) we calculate the M/L value in each radial bin. These results are also presented in Table 4.5. The M/L value is the ratio of the surface density of the isothermal old thin disc (in $M_\odot$) to the total surface brightness (in $L_\odot$).

Instrument	Mean Radius (arcsec)	Color B - I	σ_z (km s ⁻¹)	Surface Mass Density (M _⊙ pc ⁻²)	(M/L) _B	(M/L) _V	(M/L) _R	(M/L) _I	(M/L) _{3.6}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
VIRUS-W	62	1.82	55.4 ± 6.5	284 ± 87	2.8 ± 0.9	2.6 ± 0.8	2.6 ± 0.8	2.1 ± 0.7	0.9 ± 0.3
VIRUS-W	109	1.70	50.9 ± 9.0	240 ± 97	4.1 ± 1.7	3.9 ± 1.6	4.0 ± 1.6	3.4 ± 1.4	1.4 ± 0.6
PN.S	132	1.64	33.8 ± 3.8	106 ± 32	2.3 ± 0.7	2.3 ± 0.7	2.4 ± 0.7	2.0 ± 0.6	0.9 ± 0.3
PN.S	208	1.44	22.6 ± 2.5	47 ± 14	2.4 ± 0.7	2.5 ± 0.8	2.9 ± 0.9	2.6 ± 0.8	1.2 ± 0.3
PN.S	293	1.22	17.5 ± 3.6	28 ± 13	3.7 ± 1.7	4.2 ± 2.0	5.3 ± 2.5	4.9 ± 2.3	2.2 ± 1.1

Table 4.5: The results from the calculation of the surface mass density and M/L for a self-gravitating vertically exponential disc. Foreground extinction correction has been applied to the M/L values. The uncertainty in the scale height determination is the largest source of error. The columns are: (1) instrument used for the observations, (2) average radius of the radial bin (the values for the VIRUS-W bins are the luminosity-weighted radius), (3) color based on photometric data from Möllenhoff (2004), (4) vertical velocity dispersion of the hot component, (5) calculated surface mass density using the dispersion of the hot component, (6 – 10) M/L corrected for foreground extinction in different bands.

4.5.4 Stellar Surface Mass Density: isothermal model including cold component

We have measured velocity dispersions separately for the young and older disks but, for consistency with earlier work, our subsequent dynamical analysis (like most previous measurements of the disc surface density using the disc velocity dispersion) modelled the older disc as a single hot self-gravitating structure. We adopted an isothermal disc, and then used the Jeans equation via Eqn. 4.1 to measure the surface density. Identifying the two kinematical components (young and old) in the disc is a step forward, but the procedure as described above is still not entirely correct. The equilibrium of the hot disc is determined by its own gravitational field plus the gravitational field of the cold layer (gas and young stars) which we can consider as external fields. The presence of these external fields changes the vertical structure of the old disc and affects the derived surface density and M/L values for the old disc. We discuss this in more detail in Appendix B. The main result is that Eqn. 4.1 actually measures the *total* surface density (young plus old): $\sigma_z^2 = 2\pi G h_z \Sigma_T = 2\pi G h_z (\Sigma_C + \Sigma_D)$, where Σ_C is the density of the cold component (gas + cold stellar disc) and Σ_D is the density of the hot component. The derived surface density of the old disc is then a bit lower than the values given in Table 4.5.

The ‘very thin’ cold layer of the thin disc comprises gas and young stars, which we write as $\Sigma_C = \Sigma_{C,\text{gas}} + \Sigma_{C,*}$ where $\Sigma_{C,\text{gas}}$ is known directly from radio observations (e.g. Combes & Bica 1997). The stellar contribution $\Sigma_{C,*}$ is not known directly from our data. In the following section, we estimate the effect of the cold gas layer at the five radii in NGC 628 (2.6 kpc to 12.2 kpc) where we have velocity dispersion data.

From Eqn. B.10 in Appendix B, the velocity dispersion of the isothermal sheet is $\sigma_z^2 = 2\pi G h_z (\Sigma_C + \Sigma_D)$. The adopted scale height $h_z = 400$ pc, which refers to the scale height of the hot component. If h_z is constant with radius, the radial variation of σ_z^2 will follow the total surface density rather than the surface density

of the isothermal sheet. In NGC 628, the gas fraction of the total surface density is significant at larger radii (Table 4.6). The scale length for σ_z^2 should then be longer than the photometric scale length. This effect is seen in our data (see last data point in Fig. 4.6). Alternately, it is possible that this effect could be caused by other astrophysical phenomena such as heating agents (like minor mergers) that may lead to a flaring of the stellar disc, or the notion that the hot and cold stellar discs may have different scale lengths.

4.5.4.1 The Surface Density of the Cold Sheet

Our goal is to calculate the rotation curve contribution from the baryons in the disc. Assuming that the disc is a hot isothermal stellar layer Σ_D plus a thin young cold layer Σ_C , we measure the total surface density $\Sigma_T = \Sigma_C + \Sigma_D$. The cold layer Σ_C is made up partly of the gas sheet and partly of the thin young stellar disc. The cold stellar layer is thin, and the hot stellar layer is thicker, and their shape affects the calculated rotation curve. This is a second order effect, but it would be useful to know both of the stellar surface densities Σ_D and $\Sigma_{C,*}$.

The velocity dispersion analysis gives the total surface density

$$\Sigma_T = \Sigma_D + \Sigma_{C,\text{gas}} + \Sigma_{C,*}$$

of the disc. We can make an estimate of the ratio of cold to hot stellar contributions $\Sigma_{C,*}/\Sigma_D$ from our IFU study in the inner parts of NGC 628 which gives the fraction of light that comes from the two stellar components. Their M/L ratios need to be estimated from stellar population synthesis. In the outer regions, the PNe analysis gives the fraction of cold emission-line objects, but deriving the fractional mass of the underlying cold stellar population is uncertain because (a) of possible contamination of the sample by HII regions, and (b) the young PNe have more massive progenitors, and the lifetimes in the PNe phase are very strongly dependent on their progenitor masses (e.g. Miller Bertolami 2016).

Our IFU study analysed the integrated light spectrum as the sum of two velocity components (hot and cold, or young and old), without specifying the age range of either component. The age range is needed to calculate their M/L ratios, and we estimate the age ranges from the observed age-velocity dispersion relation (AVR) in the solar neighbourhood. Fig. 4.7 shows the vertical velocity dispersion σ_w vs age for the Casagrande et al. (2011) stars from the Geneva Copenhagen survey. In order to exclude most thick disc stars, the Fig. includes only stars with $[\text{Fe}/\text{H}] > -0.3$. The dispersion rises from about 10 km s^{-1} for ages $< 1 \text{ Gyr}$ to about 20 km s^{-1} at 4 Gyr and then remains approximately constant. If the AVR in NGC 628 has a similar shape, then the cold stellar component would be made up of stars younger than about 3 Gyr .

The (cold, hot) component contributions to the integrated light spectrum shown in Fig. 4.4 (close to the V-band) are given as percentages L_C/L_D in the first two rows of Table 4.6. From Bruzual & Charlot (2003), we compute the expected $(M/L)_V$ ratios for populations younger and older than 3 Gyr , assuming a disc age of 12 Gyr

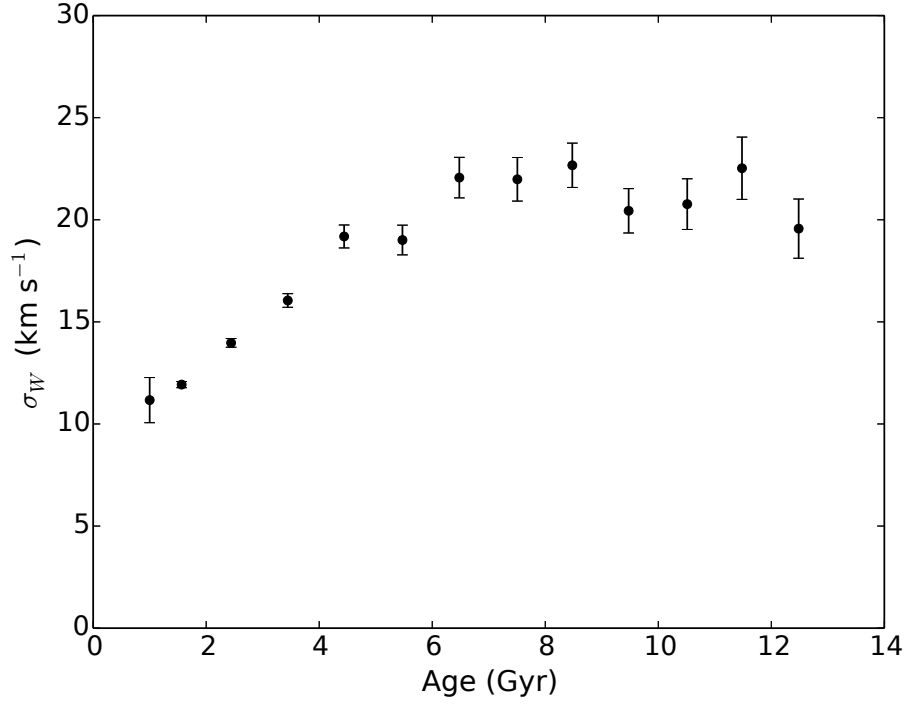


Figure 4.7: Vertical velocity dispersion σ_W *vs* stellar age for the solar neighbourhood, for stars with $[\text{Fe}/\text{H}] > -0.3$, data from Casagrande et al (2011).

and a star formation rate that decays with time like $\exp(-t/\tau)$. For $\tau > 3$ Gyr, the M/L ratios for the young and old populations vary with τ almost in lockstep, and the ratio $F_C = \Sigma_{C,*}/\Sigma_D$ is about 0.12, almost independent of τ . The surface densities of the stellar disc components are then

$$\Sigma_D = \frac{\Sigma_T - \Sigma_{C,\text{gas}}}{1 + F_C} \quad \text{and} \quad \Sigma_{C,*} = F_C \Sigma_D. \quad (4.8)$$

In the first two rows of Table 4.6, we use values of F_C derived from the (cold, hot) component contributions to the integrated light spectrum as described above. In the following rows, where the velocity dispersions come from PNe, we adopt the mean value of 0.12 for F_C from the integrated light spectra. Table 4.6 gives F_C , Σ_D , $\Sigma_{C,*}$ and finally the $(M/L)_V$ ratio for the hot component at each radius. We can compare the observed values of $(M/L)_V$ with those calculated from the Bruzual & Charlot (2003) models. The calculated $(M/L)_V$ is in the range 2.3 to 2.9 for the star formation rate parameter $\tau > 3$ Gyr, in fair agreement with our values in Table 4.6 for the old disc of NGC 628¹. Therefore, on average, the cold disc contributes $\sim 42\%$ to the total light whereas only about 10% to the total stellar mass of the disc.

¹In Appendix C, we look at the influence of the cold isothermal sheet on the surface mass density of the Milky Way disc.

R (kpc)	σ_z (km s ⁻¹)	Σ_T (M _⊙ pc ⁻²)	$\Sigma_{C,\text{gas}}$ (M _⊙ pc ⁻²)	b	L_C/L_D	F_C	Σ_D (M _⊙ pc ⁻²)	$\Sigma_{C,*}$ (M _⊙ pc ⁻²)	$(M/L)_V$	$(M/L)_{3.6}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2.6	55.4	284	16.9	0.060	44/56	0.13	236	31	2.2	0.7
4.5	50.9	240	17.2	0.072	40/60	0.11	201	22	3.3	1.18
5.5	33.8	106	16.8	0.16	42/58	0.12	80	10	1.7	0.7
8.7	22.6	47	12.7	0.28	42/58	0.12	31	4	1.6	0.8
12.2	17.5	28	8.6	0.31	42/58	0.12	17	2	2.6	1.4

Table 4.6: Parameters for NGC 628 at the five radii where the velocity dispersion of the hot disc was measured (inner two radii from integrated light, outer three from PNe). All surface densities are in units of M_⊙ pc⁻². The columns are (1) radius, (2) vertical velocity dispersion σ_z of the hot disc, (3) total surface density Σ_T from Eqn. B.10 in Appendix B, (4) observed surface density $\Sigma_{C,\text{gas}}$ of the gas layer from Combes & Becaert (1997), (5) the offset parameter b from Eqn. B.5 in Appendix B, neglecting the stellar contribution to the young disc, (6) ratio of luminosities of cold and hot layers from the integrated spectra in rows 1 and 2, and adopting the mean of rows 1 and 2 in rows 3 to 5, (7) the ratio F_C of the stellar surface densities of the cold and hot layers, (8) the surface density Σ_D of the hot layer from Eqns. 4.8, (9) the stellar surface density $\Sigma_{C,*}$ of the cold layer, (10) the $(M/L)_V$ ratio of the hot layer with surface density Σ_D , (11) The $(M/L)_{3.6}$ in the spitzer 3.6 μm band of the hot stellar disc with surface density Σ_D .

4.5.5 Rotation Curve Decomposition

4.5.5.1 Observed HI rotation curve

Obtaining the rotation curve of a near-face-on galaxy, such as NGC 628, is challenging. The uncertainty associated with the inclination is substantial and is the main contributor to the error budget of the rotational velocity. Therefore, we approach this task in several steps. First, we estimate an approximate value for the average inclination angle by placing this galaxy on the 3.6 μm Tully-Fisher relation from Ponomareva (2017). This gives us an initial guess of the inclination angle = 9°.

We then use the HI data for NGC 628 from the THINGS survey (Walter et al. 2008) to get the rotation curve for this galaxy. After smoothing and masking the original data cube, we constructed a velocity field by fitting a Gauss-Hermite polynomial to the velocity profiles. This velocity field is corrected for the skewness of the profiles, in order to remove non-circular motions, using the technique described in Ponomareva et al. (2016). We then derive the rotation curve from the velocity field by fitting a tilted-ring model (Begeman 1989), using the Groningen Imaging Processing System (Gipsy, van der Hulst et al. 1992). During the tilted ring modelling, we account for the outer warp of the disc, which can be clearly seen in the upper panel in Fig. 4.8. We find the average inclination across all radii to be 8° (Fig. 4.8, middle panel). We derive the rotation curve of the galaxy by keeping the inclination fixed at this value. The resulting rotation curve is presented in the bottom panel of Fig. 4.8, with red and blue curves indicating the receding and approaching sides of the galaxy respectively. We adopt the difference between the receding and approaching sides as the 1 σ error in the measured rotational velocity. The full error in the rotational velocity was calculated by also taking into account

the uncertainty in the inclination.

We now proceed to calculate the contribution to the observed rotation curve from the gas. An integrated column-density HI map was created by summing the primary beam-corrected channels of the clean data cube. The radial surface density profile is then derived by averaging the pixel values in the concentric ellipses projected on to the HI map. We use the same radial sampling, position and inclination as those for the rotation curve derivation.

The column density profile was then corrected for the presence of helium and metals by multiplying the measured densities by 1.4. The Gipsy task ROTMOD was used to compute the corresponding rotation curve assuming an infinitely thin exponential gas disc. As we model the disc where the matter is not spherically distributed, the net radial force from the gas can be outwards. The presence of such an outward radial force is conventionally shown by negative rotational velocities of the gas component (de Blok et al. 2008). In addition to the atomic gas, we also adopt the CO data from Combes & Becquaert (1997) to derive the rotational velocity for the molecular gas.

4.5.5.2 Stellar Distribution

One of the largest sources of uncertainty for the mass modelling is the stellar disc mass, which usually depends on the adopted M/L . However, for NGC 628 we have measured the surface density of the stellar component directly. Moreover, we can separate the surface density contributions from the old stellar disc with an adopted scale height of 400 pc from the surface density of the young kinematically cold stellar component, assuming it to be infinitely thin. To model the rotation curves of both these components, we use the Gipsy task ROTMOD, assuming an exponential disc model. The surface brightness profile of this galaxy is exponential, as shown by the S4G survey (Muñoz-Mateos et al. 2013). More directly, our surface density values Σ_D for the kinematically hot component (Table 4.6) are well represented by an exponential disc with our calculated central surface mass density value of $710 \pm 165 M_\odot/\text{pc}^2$ (section 5.1) and the scale length of 3.17 kpc from Table 4.2. We use this exponential surface density profile to model the rotation. For the kinematically cold stellar component $\Sigma_{C,*}$, we assume the ratio of the surface mass densities of the cold stellar population to the hot stellar population = 0.12 at all radii (average value of F_C for the two inner rows in Table 4.6). This approach results in a smooth rotation curve for both the stellar components.

A small bulge component is present in NGC628 (Muñoz-Mateos et al. 2013). While the total bulge light contributes only 6.5% to the total light of the galaxy, the bulge light dominates within the central 1.5 kpc and, therefore, we need to include it in our mass modelling. We take advantage of the bulge-disc decomposition modelling of the 3.6 μm profile provided by Salo et al. (2015). We then convert the bulge surface brightness into the surface mass density using the stellar M/L for 3.6 μm = 0.6 (Meidt et al. 2012; Querejeta et al. 2015; Röck et al. 2015) and $M_\odot(3.6 \mu\text{m}) = 3.24 \text{ mag}$ (Oh et al. 2008). We model the bulge using the same Gipsy task ROTMOD assuming a spherical potential. The rotation curves of all

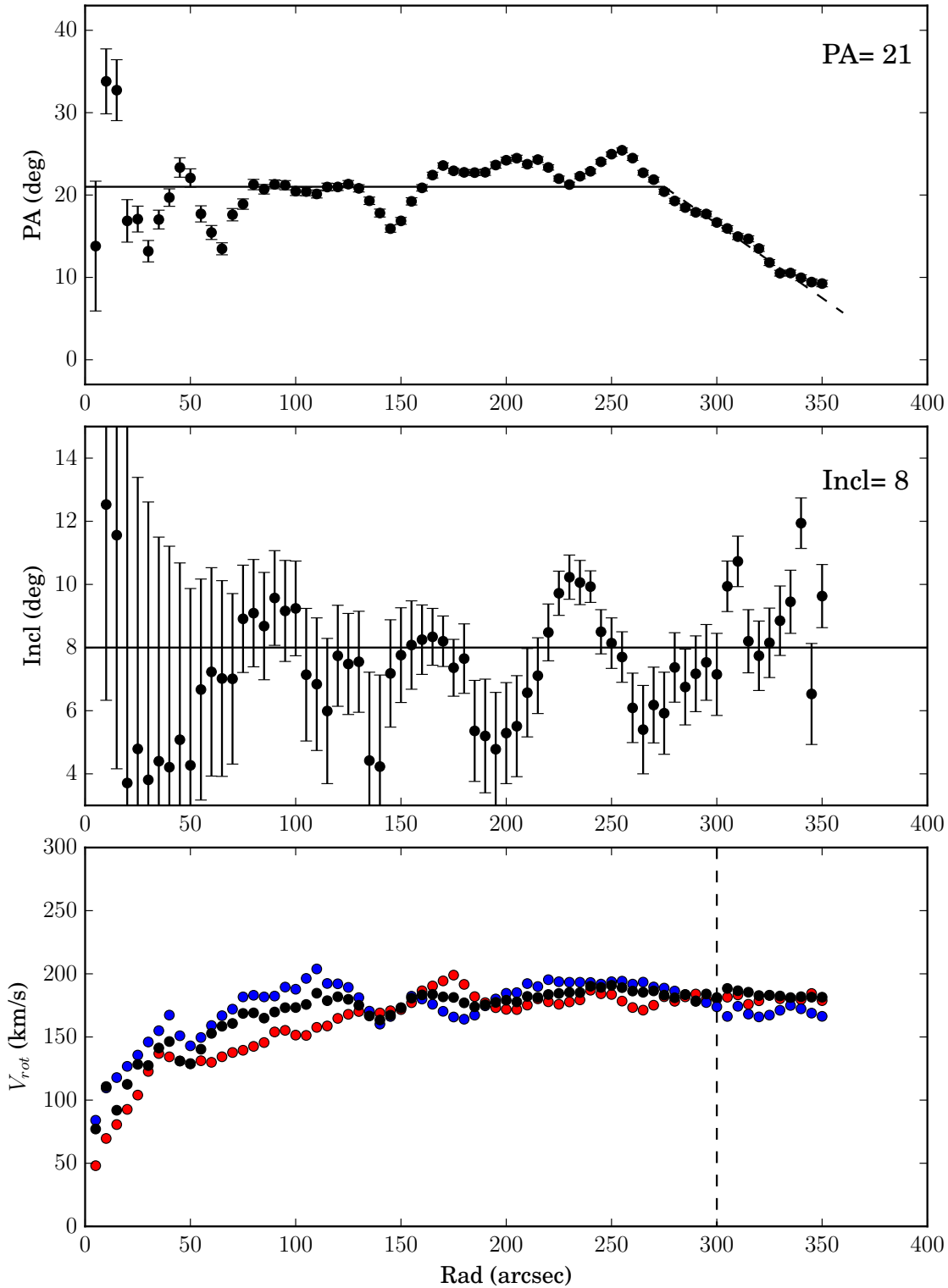


Figure 4.8: The results of the tilted-ring modelling for NGC 628. Upper panel: position angle as a function of radius. The outer warp is modelled beyond 250". Middle panel: inclination angle as a function of radius. The mean value of 8° is adopted for our analysis. Bottom panel: observed HI rotation curve is shown in black. The red and blue curves show the velocity of the receding and approaching sides of the galaxy respectively. The dashed vertical line indicates the optical radius.

the baryonic components were modelled with the same sampling as was used for the derivation of the observed rotation curve.

4.5.5.3 Mass modelling

The total rotational velocity of a spiral galaxy can be calculated using the relation:

$$V_{tot}^2 = V_{gas}^2 + V_{\star}^2 + V_{halo}^2, \quad (4.9)$$

where V_{gas} , $V_{\star}$ and V_{halo} are the rotational velocities of the gas (molecular+atomic), the stellar component and the dark halo respectively. In our case, the rotational velocity of stars is, in fact, represented by the velocities of the hot and cold stellar components: $V_{\star}^2 = V_{hot}^2 + V_{cold}^2$. As the observed HI rotation curve (V_{obs}) traces the total gravitational potential of a galaxy, we can derive the rotation curve of the dark matter halo by fitting various parameters until V_{tot} matches V_{obs} as closely as possible. Moreover, for this galaxy, we have an independently measured surface density distribution for the stellar disc components, so we do not have the usual unconstrained stellar M/L . This allows us to fix the gas and stellar rotation curves and only fit the rotation curve of the dark matter halo. This breaks the usual disc-halo degeneracy and allows us to test the maximality of the disc directly.

For our analysis we use two models of the dark matter rotation curves: spherical pISO (pseudo isothermal) and NFW-halo. The pISO halo has a central core and is parameterised by its central density (ρ_0) and the radius of the core (R_c). Its rotation curve is given by:

$$V_{DM}^{pISO}(R) = \sqrt{4\pi G \rho_0 R_c^2 \left[1 - \frac{R_c}{R} \tan^{-1}\left(\frac{R}{R_c}\right) \right]} \quad (4.10)$$

The NFW halo (Navarro et al. 1997) is parameterised by its mass (M_{200}) within the viral radius (R_{200}) and its concentration (c). Its rotation curve is given by:

$$V_{DM}^{NFW}(R) = V_{200} \left[\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)]} \right]^{1/2} \quad (4.11)$$

where $x = R/R_{200}$ and V_{200} is the circular velocity at R_{200} .

The Gipsy task ROTMAS was again used to find the rotation curves for the dark haloes. We ran the models for each of the two dark matter haloes separately, keeping the rotation curves of the gas, two stellar disc components and the bulge component fixed. The results from this modelling is presented in Fig. 4.9 (the top panel is for the pISO halo and the bottom panel for the NFW halo). Although the rotation curves for the two haloes have a similar shape, the pISO halo works marginally better in our case with a $\chi_{red}^2 = 1.52$ compared to a $\chi_{red}^2 = 1.6$ for the NFW halo. In both cases we find the disc to be maximal with $V_{disc} = 0.83V_{max}$. We note that the M/L for the bulge component remains at 0.6 even when the bulge rotation curve was not constrained to this value. The derived parameters of the fitted dark matter rotation curves are presented in Table 4.7. We note that the scale length derived for

the pISO model is rather short for a luminous galaxy such as NGC 628 (Kormendy & Freeman 2016). The error on the total rotational velocity (magenta line in Fig. 4.9) follows from the error on the central surface density described in Section 5.

pISO				NFW	
R_C (kpc)	ρ ($10^{-3} \text{ M}_{\odot} \text{ pc}^{-3}$)	χ_{red}^2	C	R_{200} (kpc)	χ_{red}^2
1.2 ± 0.3	176.6 ± 27.7	1.52	15.5 ± 2.0	124.1 ± 12.7	1.6

Table 4.7: The derived parameters of the fitted dark matter haloes from the mass modelling.

4.6 Conclusions

The disc-(dark halo) degeneracy in spiral galaxies has been an important problem in dark halo studies for several decades. One of the more direct methods of breaking this degeneracy is by measuring the surface mass density of the disc and hence its mass-to-light ratio, using the velocity dispersion and the estimated scale height of the disc. However, it is essential that the measured vertical velocity dispersion and the disc scale height pertain to the same stellar population.

In the disc of a typical star-forming spiral galaxy, the colder young stellar component provides a significant contribution to the number density of kinematical tracers like red giants and planetary nebulae which have stellar progenitors with a wide range of ages. Through its red giants, which are a significant contributor to the integrated light spectra that are used for velocity dispersion measurements, the colder young population can have a substantial influence on the observed vertical velocity dispersion of the disc.

The other observable, the scale height of the disc, is usually measured from red or near-IR surface photometry of edge-on galaxies, away from the central dust layer. The estimated scale heights are then close to the scale heights of the older disc population.

Using integrated light absorption line spectra and velocities for a large sample of PNe in the face-on disc galaxy NGC 628, we show that the velocity distribution of disc stars does indeed include a young kinematically cold population and an older kinematically hotter component. We argue that previous integrated light and PNe studies have underestimated the surface density and M/L ratio of disks because they were not able to account for the contribution from the younger colder disc population in their velocity dispersion analysis.

To estimate the surface density of the disc, the dispersion of the hotter component of the disc is needed, in combination with the old disc scale height estimated from red or near-IR photometry of edge-on galaxies. For NGC 628, this leads to a surface mass density that is ~ 2.7 times larger than the values derived from previous estimates of disc density from disc velocity dispersions. This factor agrees well with our earlier

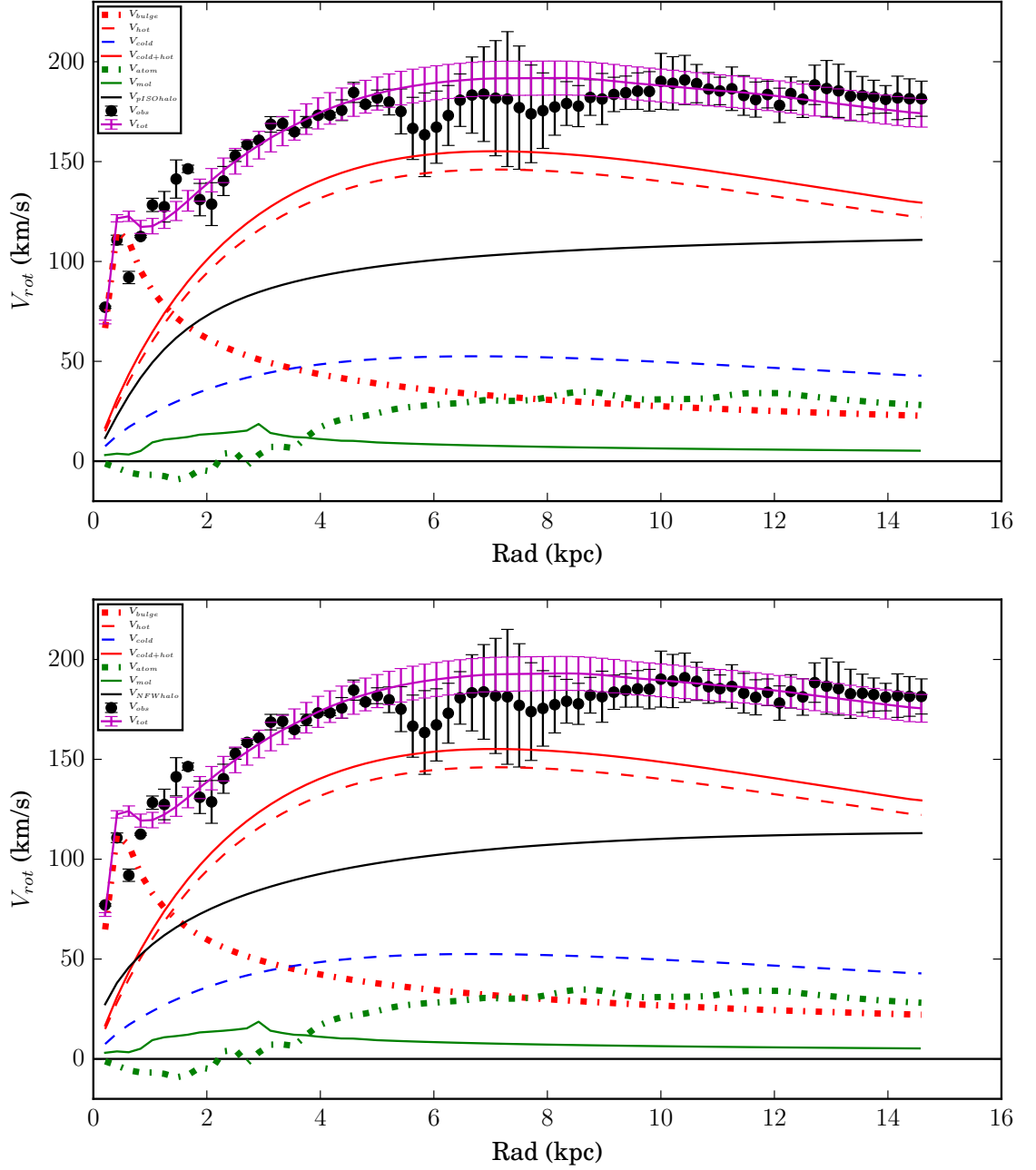


Figure 4.9: The rotation curve decomposition for NGC 628 by fitting a pISO halo (top panel) and a NFW halo (bottom panel). Observed HI rotation curve is shown as black dots. The rotational velocity of the atomic gas and molecular gas is shown in green as dashed-dotted and solid curves respectively. The rotation curve for the bulge is shown by the red dashed-dotted line. The hot and cold stellar disc rotational velocities are indicated using the dashed red and blue curves respectively. The solid red line represents the combined rotation velocity of the two stellar components (hot+cold). The fitted dark matter halo rotation curve is shown by the black solid line. The magenta line represents the total rotational velocity: $V_{tot}^2 = V_{gas}^2 + V_{hot}^2 + V_{cold}^2 + V_{halo}^2$.

estimates for the solar neighbourhood (Aniyan et al. 2016), and is large enough to make the difference between concluding that a disc is maximal or sub-maximal.

We find that the observed vertical velocity dispersion of the hotter component follows the expected exponential radial decrease, with a scale length of twice the galaxy's photometric scale length. This indicates that the M/L in this galaxy is close to constant over the radial region probed by our study ($R/h_R \approx 1$ to 4), consistent with the M/L values measured directly. Table 4.5 provides M/L values for the disc of NGC 628 at several radii and in several photometric bands, excluding the effect of the cold layer to be consistent with previous analyses. However, in reality, in the presence of the cold (gas + star) layer Σ_C , the isothermal sheet has the form

$$\rho(z) = \frac{\sigma_z^2}{8\pi G h_z^2} \operatorname{sech}^2(|z|/2h_z + b)$$

where $\tanh(b) = 2\pi G h_z \Sigma_C / \sigma_z^2$. The total surface density Σ_T then becomes $\Sigma_C + \Sigma_D = \sigma_z^2 / (2\pi G h_z)$. We find that the ratio $F_C = \Sigma_{C,*} / \Sigma_D$ appears to be about 12% in the inner regions of NGC 628, and our calculated M/L_V for the hot disc appears to be constant with radius. The larger M/L that we derive for this galaxy compared to previous studies, points towards this galaxy being a maximal disc.

Decomposing the rotation curve of this galaxy, after taking into account the hot and cold stellar components, leads to a clearly maximal disc. The rotation of the disc is 83% of the total rotational velocity of this galaxy.

In the next chapter, I extend this analysis to the spiral galaxy NGC 6946. NGC 6946 is closer than NGC 628, which provides a potential advantage with the quality of the data acquired. However, this galaxy is more inclined than NGC 628, which presents its own set of challenges. These are discussed in detail in Chapter 5.

NGC 6946

5.1 Introduction

In this chapter, I discuss the observations carried out on NGC 6946 to extract a two component velocity dispersion for the motion of the old and young disc components independently. NGC 6946 is a nearby ($D = 6.1$ Mpc) disc galaxy. NGC 6946 has a high star formation rate, $SFR = 4.76 \text{ M}_{\odot} \text{ yr}^{-1}$ (Lee 2006), which ~ 4 times the SFR of NGC 628. This galaxy has an inclination $\sim 37^{\circ}$, which makes it more inclined than NGC 628. This brings in a new challenge, as it gets harder to separate the in-plane dispersion components (σ_R and σ_{ϕ}) from the vertical dispersion (σ_z), which is needed to calculate the surface mass density of the disc. However, NGC 6946 is closer than NGC 628: we can achieve higher SNR data for the PNe which helps in our double Gaussian decomposition. We also note that NGC 628 was analysed by Herrmann & Ciardullo (2009b), and we adopted all of their basic parameters for this galaxy (scale length, scale height, distance) to compare our two-component results with their single component fits. However, they did not have good enough data for NGC 6946 to carry out a comprehensive analysis (Herrmann et al. 2008). We will only adopt the distance that they determined ($D = 6.1 \pm 0.6$ Mpc) and need to independently identify the best values for the other parameters from available literature.

As for NGC 628, explained in Chapter 4, we observed NGC 6946 using the VIRUS-W spectrograph in the inner parts of the galaxy and carried out complementary observations on the PN.S out to a radius of ~ 4 disc scale lengths. This chapter is structured like Chapter 4 – Section 5.2 describes the observations and data reduction for VIRUS-W, and section 5.3 summarises the same for the PN.S. Section 5.4 details the double Gaussian decomposition to extract the vertical velocity dispersion for the hot and cold components. Section 5.5 describes the calculation of the disc surface mass density, using the dispersion for the hot component and its implications for the rotation curve decomposition, and section 5.6 lists the conclusions from this study for NGC 6946.

5.2 VIRUS-W Spectrograph

5.2.1 Observations

VIRUS-W observations for NGC 6946 were carried out in October 2014. We were only able to get good quality data for 4 fields which were positioned on the galaxy at a luminosity weighted radius of about 1 radial scale length. Our IFU positions on the galaxy are shown in Fig. 5.1.

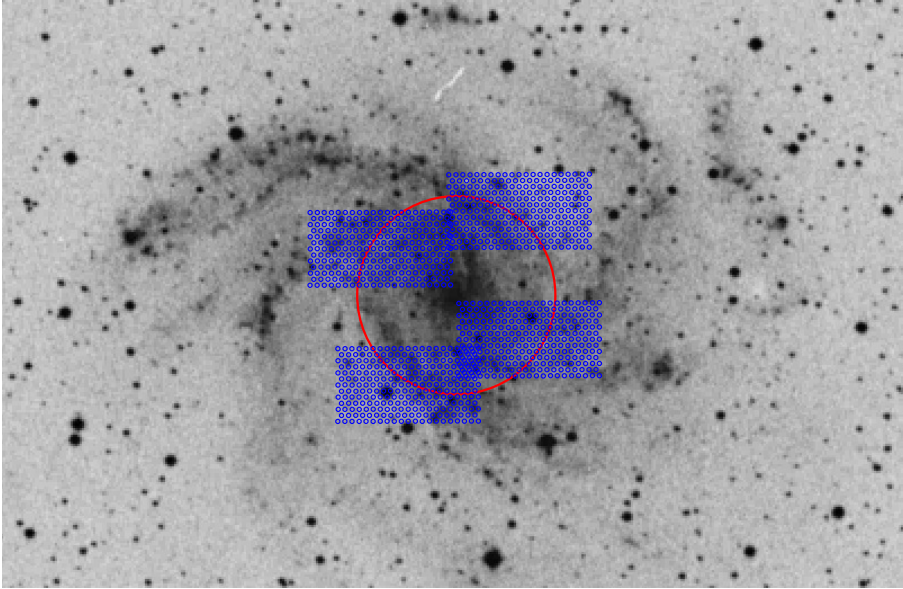


Figure 5.1: The positions of the VIRUS-W IFU fields overlaid on a DSS image of NGC 6946. The position of the 267 fibres in each field are also shown. The red circle at $75''$ shows where we separated our data into the inner and outer radial bin.

The position and exposure time at each position is given in Table 5.1. We again carried out a sky – galaxy – sky observing sequence. This sequence was repeated at least thrice at each field, as indicated in column 3 of Table 5.1. This enabled very good sky subtraction using the automated pipeline developed for VIRUS-W.

RA (J2000)	Dec (J2000)	Exposure Time (s)
20:34:54.04	+60:08:04.8	3×800
20:34:47.25	+60:10:23.8	3×800
20:34:47.13	+60:08:48.4	3×800
20:34:56.34	+60:10:01.6	3×800

Table 5.1: Coordinates and exposure times for the IFU fields in NGC 6946.

We used the CURE reduction pipeline to get the sky subtracted 1D spectrum at each of the four fields. The σ_z is expected to decline exponentially with twice the galaxy’s radial scale length. Since the fields cover a large radial extent on the galaxy, we decided to split the data into two radial bins, at luminosity-weighted radii of $54''$ and $98''$ respectively. We therefore ended up with two ‘final’ 1D spectra that we use to extract the velocity dispersions from the absorption lines.

5.3 Planetary Nebula Spectrograph

5.3.1 Observations and Velocity Extraction

The data for NGC 6946 were acquired during the same observing run as for NGC 628, in September 2014. The weather during the run was excellent, with typical seeing of $\sim 1''$. We employed the same observing strategy as in the case of NGC 628. We obtained 11 images centred on the centre of the galaxy, each with an exposure time of 1800s.

We used the PN.S data reduction pipeline (described in Chapter 3) to get the final stacked 'left' and 'right' image for the [OIII] data. Identifying the unresolved objects on the left and right stacked images gives us the radial velocity of these sources. We also observed NGC 6946 in $H\alpha$, using the $H\alpha$ narrow band filter on the undispersed $H\alpha$ arm of the PN.S. We then used the [OIII] stacked images along with the $H\alpha$ stacked image to identify the PNe candidates in this galaxy.

5.3.2 Identification of Sources

Chapter 3 details how we identify the 'true PNe' candidates in our galaxies (also see Arnaboldi et al. 2017). We identified 444 unresolved objects with [OIII] emission in this galaxy. From the measured positions of these sources on the left and right images, astrometric positions and LOS velocities were derived simultaneously.

We converted our instrumental magnitudes into the m_{5007} magnitude scale using our spectrophotometric standards (Eqn. 3.1 from Chapter 3). We also corrected these magnitudes for foreground extinction using Schlafly & Finkbeiner (2011) dust maps. The bright luminosity cut-off for PNe in this galaxy is expected to be $m_{5007} = 23.22$. Fig. 5.2 shows the luminosity function for NGC 6946, including all identified unresolved sources. The dashed line in the plot shows the position of the bright luminosity cut-off for the PNe.

Our sample of 444 identified sources is still a mixture of HII regions and PNe, since both can have strong [OIII] emissions. We again use our empirical relationship between the [OIII] – $H\alpha$ colour and m_{5007} magnitude (as detailed in Chapter 3) to discriminate between PNe and HII regions.

In addition to HII regions, the historical supernovae are a potential source of contamination. NGC 6946 has an unusually high number of historical supernovae. According to the IAU Central Bureau for Astronomical Telegrams (CBAT) List of Supernovae website (<http://www.cbat.eps.harvard.edu/lists/Supernovae.html>), there are nine known historical supernovae in NGC 6946. None of these objects made it into our PNe sample. We had one unresolved [OIII] source at $\sim 3''$ from the historical supernova SN 2002hh. However, on applying our colour-magnitude cut, this object was classified as an HII region. Thus, we don't have any of these contaminants in our final PNe sample.

We already estimated the measuring errors associated with the PNe radial velocities using our data for NGC 628. This estimate can be applied to all our samples. We, therefore, typically estimate our measuring errors to be $< 9 \text{ km s}^{-1}$ in NGC

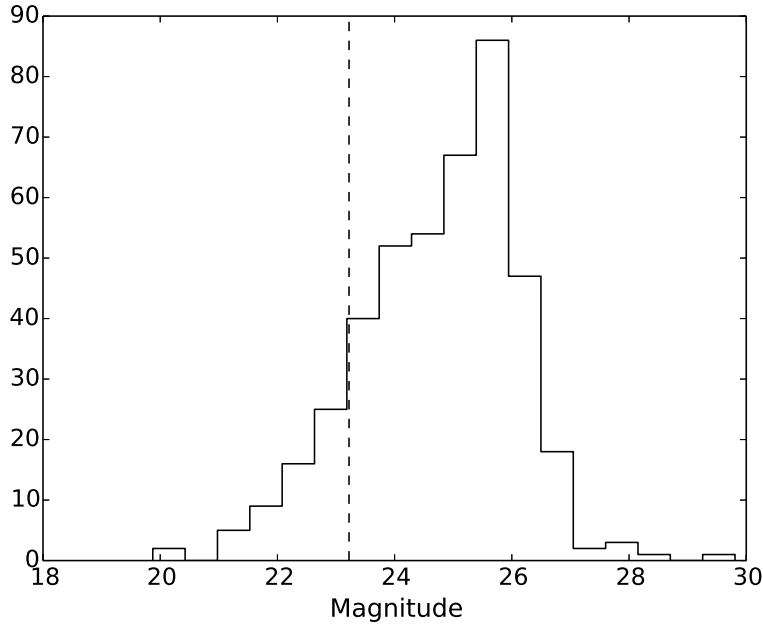


Figure 5.2: The luminosity function for all spatially unresolved [OIII] emitters identified in the combined left and right images of the PN.S for NGC 6946. The dashed line shows the expected bright luminosity cut-off for PNe. Objects brighter than the cut-off are most probably bright HII regions.

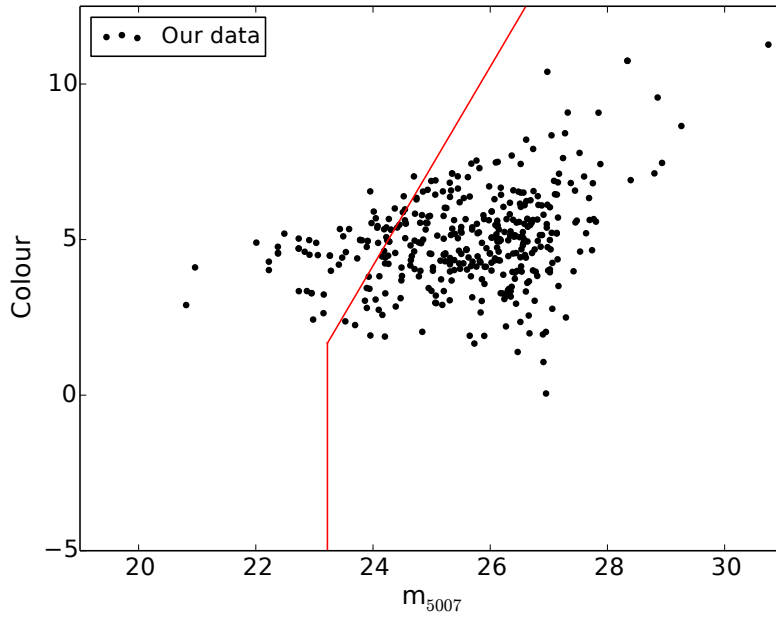


Figure 5.3: The colour-magnitude plot for NGC 6946. The vertical axis is the [OIII] - $H\alpha$ colour and the horizontal axis is the m_{5007} magnitude. The PNe lie to the right of the red lines. Only these objects are used in our analysis.

6946 as well (see section 4.3.3 in Chapter 4).

5.4 Extracting Velocity Dispersions of the Hot and Cold Components

Prior to proceeding with our double Gaussian decomposition for this galaxy, we need to obtain certain parameters from literature. NGC 628 was analysed by Herrmann & Ciardullo (2009b), and we could use all the parameters used by them for a direct comparison with their results. Herrmann & Ciardullo (2009b) did not have good enough data to extract a vertical velocity dispersion for NGC 6946. They did, however, estimate a distance to the galaxy (Herrmann et al. 2008). We adopt their distance of $D = 6.1 \pm 0.6$ Mpc for our analysis. We note that this distance is a bit larger than the median NED distance of 5.4 Mpc.

We estimated the inclination and position angle (PA), based on kinematic fits to the THINGS HI data (Walter et al. 2008) for this galaxy. The values for the inclination and PA from the PNe agree well with the values obtained from the HI data. This indicates that there is no evident disconnect between the gaseous HI disc and the stellar disc, at least within the radii for which we have data. Fig. 5.4 shows the kinematic fit to the HI data to obtain the values of inclination and PA. We adopt the value for scale length from Larsen & Richtler (1999). They get an R-band scale length = $80''$ from their photometric data. Table 5.2 summarises the values that we use for the various parameters of this galaxy.

Parameters	Value	Source
Scale length (R - band)	$80.0''$	Larsen & Richtler (1999)
Distance	6.1 ± 0.6 Mpc	Herrmann et al. (2008)
Inclination	37°	Kinematic fit to HI data from Walter et al. (2008)

Table 5.2: The parameters for NGC 6946 adopted from the literature and used in our analysis.

5.4.1 Stellar Absorption Spectra

5.4.1.1 Removing Galactic Rotation

As for NGC 628, we used the 21 cm HI data from the THINGS survey (Walter et al. 2008) to subtract the local HI velocity at the position of each fibre to remove galactic rotation. This will get rid of any large scale streaming motions across the IFU. We carried out tests to check if removing the galactic rotation by modelling the rotation field over the entire IFU using the observed rotation curve is a better option. However, when we did this, the line-of-sight velocity dispersions (v_{LOS}) were larger. Since larger dispersions are an indication that the rotation hasn't been so well subtracted, we decided to use the local HI velocity to remove rotation. This technique will however introduce an additional small component of velocity dispersion to the apparent stellar velocity dispersion, because the HI mean velocities

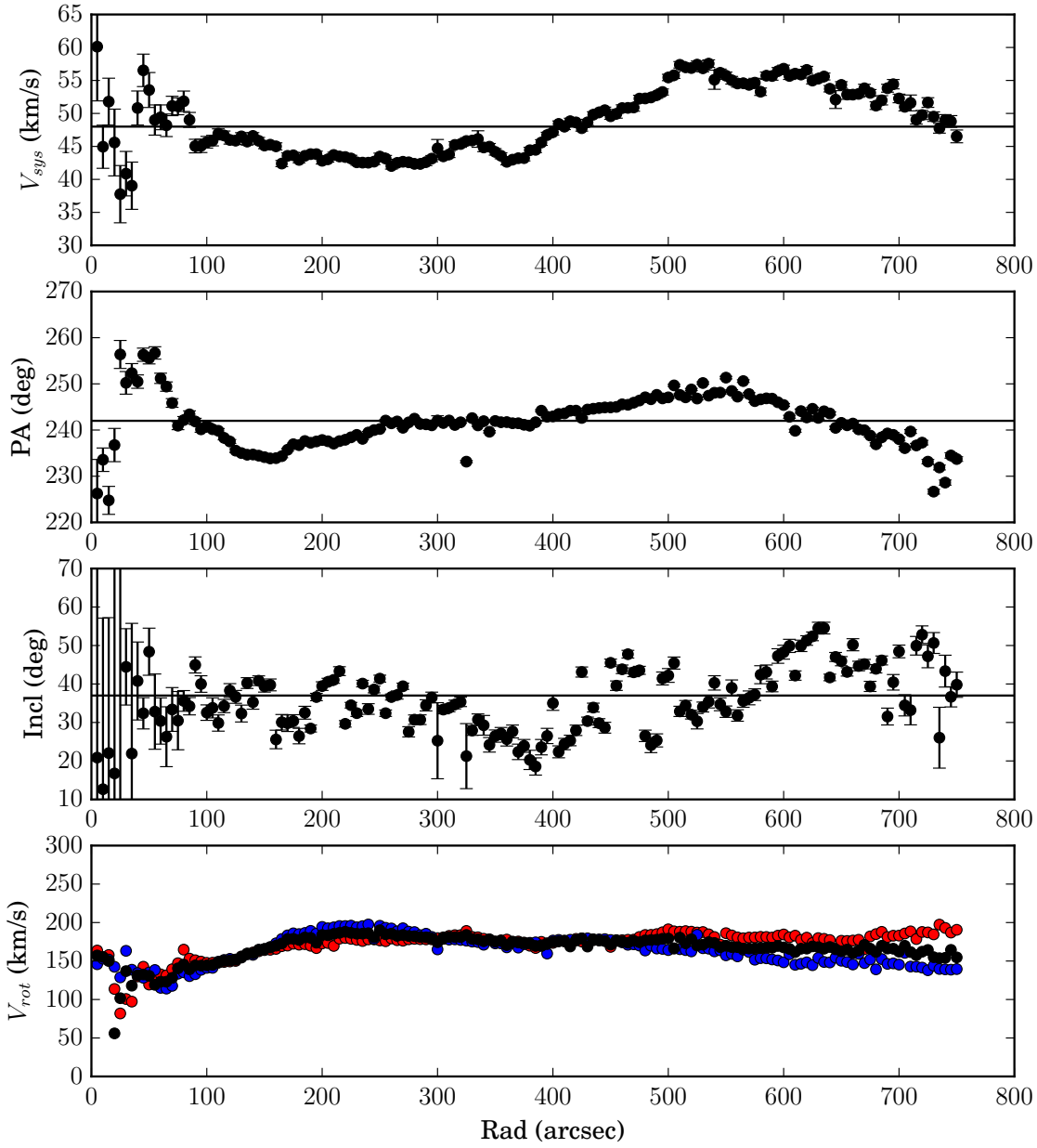


Figure 5.4: Kinematic fits to the HI THINGS data for NGC 6946. The top three panels show the systemic velocity, position angle and inclination as a function of radius. The bottom panel shows the HI rotation curve of the galaxy. The blue and red data points are for the approaching and receding side of the galaxy respectively. The black curve is the average rotation curve for both sides.

themselves have a small velocity dispersion. We correct our derived stellar dispersion for this effect.

The VIRUS-W IFUs cover a large radial extent in the galaxy. Since the vertical velocity dispersion (σ_z) is expected to fall exponentially with twice the galaxy's scale length, we don't want each radial bin to be too large. We divide our IFU data into two radial bins corresponding to a luminosity weighted radius of 54" and 98".

NGC 6946 is more inclined than NGC 628, and the asymmetric drift may contribute more significantly. The stellar component tends to rotate slower than the gaseous component and ignoring to factor this effect in our analysis can lead to us measuring larger σ_{LOS} than the true intrinsic dispersion of the galaxy. In each IFU field, we split the 267 fibres into a grid of six cells, each with about 44 fibres. The gradient in asymmetric drift is negligible across the small area of a cell. We sum the spectra from all fibres in a cell. This gives us 6 spectra, one from each cell. We then cross-correlated five of the spectra against the sixth. This gives the shift in velocity to apply to the five spectra to match the spectrum from the sixth grid. This will get rid of any differential asymmetric drift across the IFU fields. We did this for all four IFU fields on the galaxy. The cross-correlated, asymmetric drift corrected spectra were then shifted to redshift $z = 0$, before summing up to get the final spectra to analyse.

This approach is not perfect – the hot and cold components will have slightly different asymmetric drifts. Also, at opposite ends of the major axis, the asymmetric drifts will be in opposite senses. These problems are expected to be minor for a galaxy with an inclination of 37° , but could be an issue for more inclined galaxies.

We decided to check the spectrum from the inner and outer radial bin for any contribution from the thick disc. When we tried to fit a third Gaussian to the spectra, the information criterion used to judge the best model clearly preferred the two component fit for the outer radial bin spectrum. However, the inner radial bin data seemed to slightly prefer a third component. The bayesian information criterion (BIC) that we use to judge models, seemed to prefer the three component fit but only by a very small margin. This margin is not enough to conclusively select the three component fit over the two component. We then realised that if we choose a three-component dispersion analysis, the dispersion of the 'hot thin disc' in the inner radial bin leads to a total surface density that is lower than the surface density of the molecular gas at the same radius (Crosthwaite & Turner 2007). Since this is an unrealistic scenario, we concluded that there is no significant thick disc contribution in our VIRUS-W data. We therefore only fit two Gaussians to the VIRUS-W data.

The final summed spectra used in our analysis have an SNR of 105 and 77 per wavelength pixel for the spectrum from the inner and outer radial bins respectively (each wavelength pixel is $\sim 0.19 \text{ \AA}$). As in the case of NGC 628, we only used the region between wavelengths of about 5050 – 5300 $\text{\AA}$ in our analysis, since it has the highest resolution and avoids the emission lines at lower wavelengths. The [NI] doublet emission lines from the interstellar medium of the galaxy can be seen at $\sim 5200 \text{ \AA}$ (see Fig. 5.5). The two weak [NI] lines come from the ISM of the galaxy as they appear at the redshift of the galaxy. The two stronger [NI] lines

that overlap them are residual sky lines. The spectrum from one of our fields had these residual sky lines. The sky subtraction routine failed to remove these strong sky lines, however it did an excellent job with removing all other sky lines. Sky subtraction has worked very well for the galaxy continuum, since we don't see any other lines that are not at the redshift of the galaxy. Since the emission line region are omitted from the analysis, having these sky lines in the spectrum does not affect our results.

5.4.1.2 LOSVD and the Vertical Velocity Dispersion

We used pPXF to obtain the mean line-of-sight velocity and the σ_{LOS} for the two Gaussians for our two VIRUS-W spectra. We did a Gaussian fit to the data, fitting two moments for each component and compared it with the results from a single component fit. The Bayesian Information Criterion (BIC; Schwarz 1978) was used to judge the preferred model for the spectra (see Eqn. 4.2 and Eqn. 4.3 in Chapter 4 on how to calculate BIC).

The BIC applies a penalty for models with a larger number of fitted parameters. Therefore, between 2 models, the model with the lower BIC value is preferred. The one Gaussian and two Gaussian fit results are tabulated in Table 5.3. Since the model with the lower value of BIC is preferred, the two component fit is preferred over the single component fits in both of the radial bins.

pPXF found an excellent fit to our spectrum, as shown in Fig. 5.5. It returns the adopted spectra of the individual components, and the 2 spectra that it returns are consistent with the spectra of red giants. The mean contributions of the cold and hot disc components to the total light are 52% and 48% in the inner radial bin and 46% and 54% in the outer bin.

Since we used the THINGS HI data to remove rotation across the fields, we need to correct these two dispersion values for the contribution from the HI velocity dispersion. This is the scatter in the HI data in the IFU fields and is different from the HI second moment. This correction was determined to be $\sim 6 \text{ km s}^{-1}$. This scatter is larger than the scatter that we found for NGC 628 ($\sim 2.5 \text{ km s}^{-1}$).

The errors given in Table 5.3 are the 1σ errors obtained from monte carlo simulations. This was done by running 1000 iterations where, in each iteration, random Gaussian noise appropriate to the observed SN of the IFU data was added to the best fit spectrum originally returned by pPXF. pPXF was run again on the new spectrum produced in each iteration. The errors are the standard deviations of the distribution of values obtained over 1000 iterations.

We, again, calculate the vertical component of the stellar velocity dispersion σ_z from the line of sight component σ_{LOS} using the following equation:

$$\sigma_{LOS}^2 = \sigma_\theta^2 \cos^2 \theta \cdot \sin^2 i + \sigma_R^2 \sin^2 \theta \cdot \sin^2 i + \sigma_z^2 \cos^2 i + \sigma_{meas}^2 \quad (5.1)$$

where σ_R , σ_θ and σ_z are the three components of the dispersion in the radial, azimuthal and vertical direction, σ_{meas} are the measurement errors on the velocity and i is the inclination of the galaxy ($i = 0$ is face-on). For the part of the rotation curve that is close to solid body, we adopt $\sigma_R = \sigma_\theta$ using the epicyclic approximation and

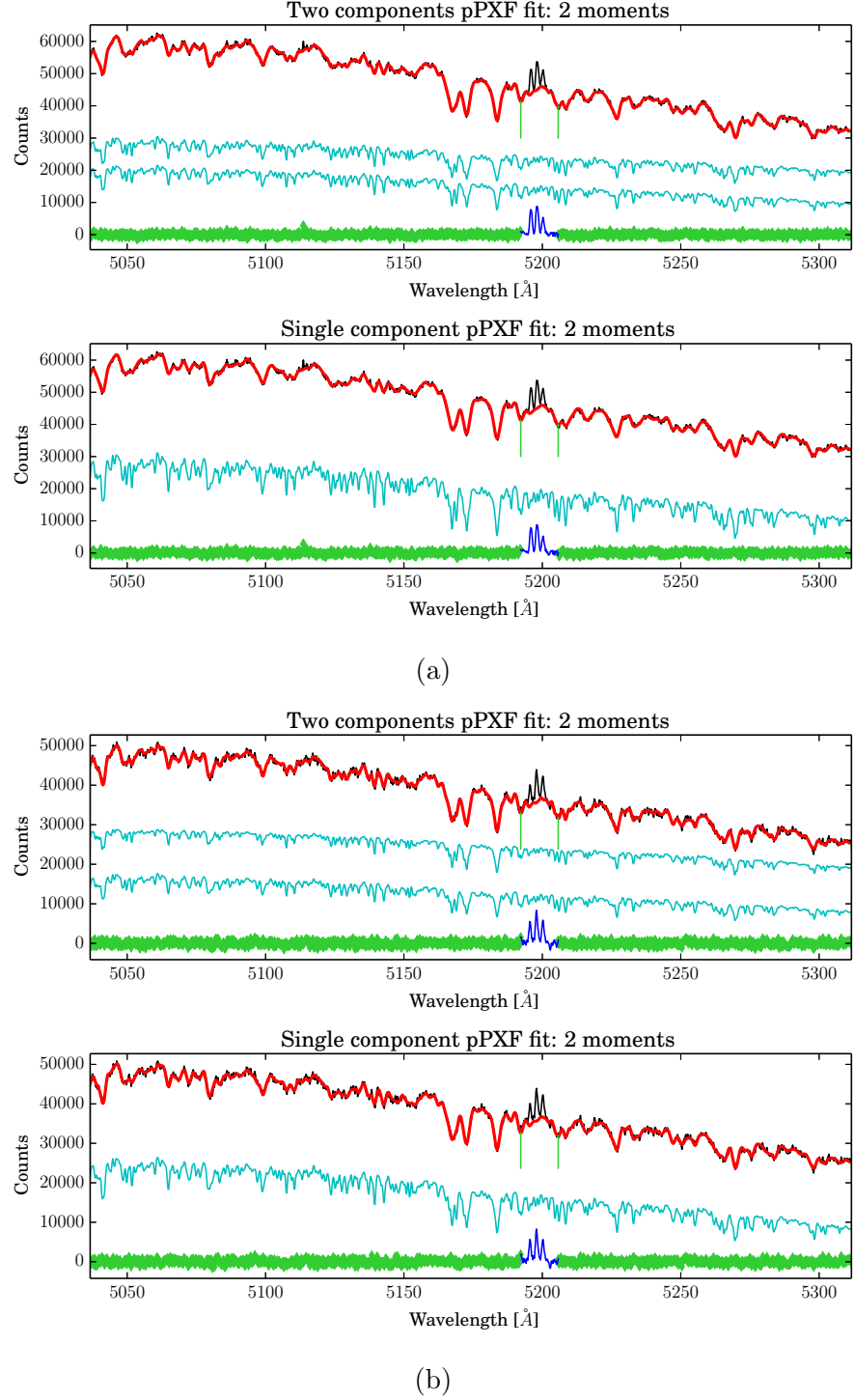


Figure 5.5: The pPXF fit results in (a) the inner radial bin at a luminosity weighted distance of 54'' and (b) the outer bin at a luminosity weighted distance of 98''. The upper panel shows the 2 component fit to the data whereas the lower panel shows a single component fit. Only the high resolution Mgb region of the spectrum was used for the fit. The galaxy spectrum is in black and the best fit from pPXF is in red. The cyan spectra are the two and one component spectra that pPXF found. The cyan spectra have been shifted vertically so as to be clearly visible. The residuals are shown in green. The [NI] doublet emission lines at ~ 5200 Å have been omitted from the fit.

for the part of the rotation curve that is flat, we make use of the epicyclic approximation and use $\sigma_R = \sqrt{2}\sigma_\theta$. Based on an examination of the THINGS HI velocities along the galaxy's kinematic major axis (last panel in Fig. 5.4) we determine this galaxy's rotation curve at radius $\leq 200''$ to be solid body and beyond $200''$ to have a flat rotation curve. We also adopt the σ_R/σ_z ratio to be 1.7, which is consistent with the value used by Bershadsky et al. (2010b) and the value found in the solar neighbourhood. Eqn. 5.1 then gives σ_z in terms of σ_{LOS} .

We also correct the σ_z values for the small broadening introduced by subtracting the local HI velocity to remove galactic rotation. Our results for the stellar σ_z values are presented in Table 5.3. The errors are the 1σ errors from monte carlo simulations (as explained in section 5.4.1.2).

Mean Radius (arcsec)	2 Component model				1 Component model		
	$\sigma_{z,cold}$ (km s ⁻¹)	$\sigma_{z,hot}$ (km s ⁻¹)	BIC	χ^2_{red}	σ_z (km s ⁻¹)	BIC	χ^2_{red}
54	26.6 ± 3.2	65.3 ± 8.3	17164	1.225	39.7 ± 1.0	17283	1.410
98	19.3 ± 2.2	64.6 ± 8.8	17351	1.231	29.3 ± 1.2	17462	1.380

Table 5.3: The single and double Gaussian fit from pPXF. For each component, the table gives the vertical velocity dispersion σ_z for each of the components. Dispersions have been corrected for the contribution from the HI velocity dispersion. An estimate of the reduced χ^2 and the Bayesian Information Criterion parameter BIC is also given. The BIC prefers the two component model in both radial bins.

5.4.2 Planetary Nebulae

5.4.2.1 Removing Galactic Rotation

Similar to the analysis of the IFU integrated light absorption spectra, we again need to remove the effects of galactic rotation from the PNe velocity field. We used the THINGS HI data as before, and obtained the HI velocity at the position of all our PNe from the THINGS first moment data. The local HI velocities were then subtracted from the PNe velocities.

These velocities, corrected for the galactic rotation, are henceforth denoted v_{LOS} . They are the velocities that are used in our analysis to calculate the velocity dispersions. As for the VIRUS-W data, the radius and azimuthal angle (θ) of the PNe in the plane of the galaxy were calculated using our estimated PA and angle of inclination, and the v_{LOS} data were then radially binned into 3 bins, each with about 125 PNe. Fig. 5.6 shows the v_{LOS} vs θ plots in each radial bin before and after the HI velocities were subtracted off.

5.4.2.2 LOSVD and the Vertical Velocity Dispersion

In each radial bin, we remove a few obvious outliers, based on a visual inspection of the velocity histogram of the objects in each bin. These outliers could be halo PNe or thick disc objects, and should be removed from our sample. Only a small number

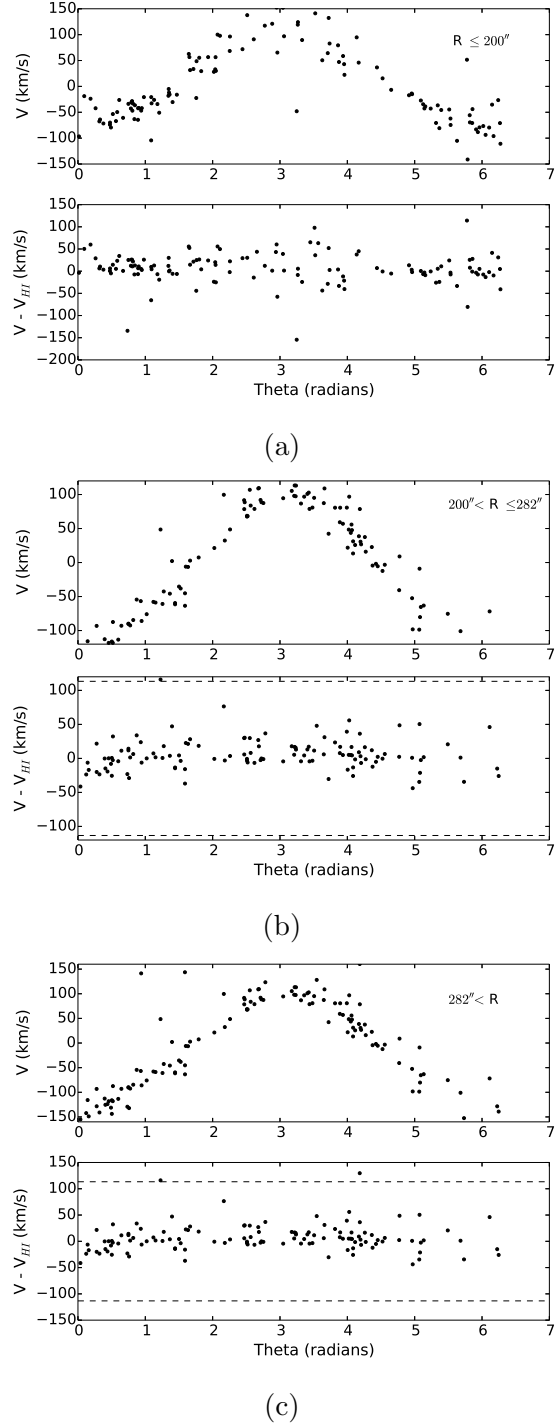


Figure 5.6: Velocity vs azimuthal angle plots in 3 radial bins, each with about 125 PNe. The angle θ is in the plane of the galaxy, measured from the line of nodes. The top panels show the velocity before taking off the local THINGS velocity and the bottom panels show the velocities after correcting for galactic rotation. A few outliers were removed based on a visual inspection of the velocity histogram of the objects in each bin. The objects within the dashed lines are the ones that were included in our sample for analysis; no objects were thrown out in the first bin. Each panel shows a mix of cold population of spatially unresolved emission line objects, plus a hotter population whose velocity dispersion appears to decrease with galactic radius.

of objects in each radial bin were discarded. The first radial bin for objects with $R \leq 200''$ had no outliers. A maximum likelihood estimator (MLE) routine written in python was then used to calculate the LOS velocity dispersions and the subsequent σ_z in each radial bin.

The first iteration in this routine estimates σ_{LOS} for the kinematically cold and hot component by maximizing the likelihood for the two-component probability distribution function given by Eqn. 4.5 (see Chapter 4).

In order to calculate the surface mass density using Eqn. 4.1, we need the vertical velocity dispersion of the hot component. To determine this value, we use a second MLE python routine. Two parameters are passed to the function in this stage: σ_{z1} and σ_{z2} which are the vertical velocity dispersions of the cold and hot components respectively. The σ_{LOS} values obtained using the method described in Eqn. 4.5 are passed to the routine as initial guesses, since the σ_z will be very close to the value of σ_{LOS} for this galaxy. We assume $f = \sigma_R/\sigma_z = 1.7$ (Bershady et al. 2010b) and use inclination $i = 37^\circ$ as explained in Table 5.2. The P.N.S data for the first radial bin are all at radii $< 200''$, where the rotation curve is close to solid body. In this bin, we assume the radial and azimuthal components of the velocity dispersion are equal i.e. $\sigma_R = \sigma_\theta$. The P.N.S data for the second and third radial bin are all at radii $> 200''$ where the rotation curve is flat and we use: $\sigma_R = \sqrt{2}\sigma_\theta$, where σ_R and σ_θ are the in-plane dispersions in the radial and azimuthal directions. Now there is only one unknown σ_z , which we need to calculate.

Once the initial guesses are passed to the routine, it calculates the expected σ_{LOS} for the hot and cold component at each azimuthal angle (θ) using the relation:

$$\begin{aligned}\sigma_{LOS1}^2 &= \frac{\sigma_{z1}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 \cos^2 i \\ \sigma_{LOS2}^2 &= \frac{\sigma_{z2}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 \cos^2 i\end{aligned}$$

The subscript 1 and 2 refers to the components of the cold and hot populations respectively. Just as in the case of NGC 628, the code then proceeds to calculate the probability of a particular v_{LOS} to be present at that azimuthal angle via the equation:

$$\begin{aligned}P &= \frac{N}{\sigma_{LOS1}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_1 \cos \theta \cdot \sin i)^2}{2\sigma_{LOS1}^2}\right) + \\ &\quad \frac{1-N}{\sigma_{LOS2}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_2 \cos \theta \cdot \sin i)^2}{2\sigma_{LOS2}^2}\right)\end{aligned}\tag{5.2}$$

In Eqn. 5.2, N is the value of the fraction of the cold population returned by the routine that calculated σ_{LOS} described earlier. μ_1 and μ_2 are associated with the means of the two components. The $\cos \theta \cdot \sin i$ term factors for any asymmetric drift present in the data. Whether we let the code estimate the terms μ_1 and μ_2 or if we fix these terms at 0, it made negligible difference to the dispersions. This shows that there is negligible contribution from the asymmetric drift in the data in each of our radial annuli. Eqn. 5.2 is maximised to return the best fit values for

σ_z for the hot and cold population of PNe. The 1σ errors are calculated similar to the method used in the analysis of the VIRUS-W data. We carried out our monte carlo error estimation by using the double Gaussian distribution found by our MLE code, to extract about 125 random velocities (i.e same number of objects as in each of our bins). We then used this new sample to calculate the σ_z of the hot and cold component using our MLE routines. This whole process was repeated 1000 times, recording the dispersions returned in each iteration. The 1σ error is then the standard deviation of the distribution of the dispersions returned from these 1000 iterations.

The vertical velocity dispersions for the two components returned from the MLE routine that is given in Table 5.4. Fig. 5.7 shows the σ_z vs radius for NGC 6946 for the hot and cold component. We also plot the dispersions from the one component model, which assumes a single homogeneous population of tracers. Unfortunately, there are no Herrmann & Ciardullo (2009b) results to compare with for this galaxy. The two inner data points come from the VIRUS-W spectra. Similar to the VIRUS-W analysis, we need to correct the dispersions for the PNe, because of the scatter in the the local THINGS HI velocity which we used to remove the galactic rotation. This correction was done as for the IFU data analysis by quadratically subtracting this small dispersion ($\sim 6 \text{ km s}^{-1}$) from the values of the vertical velocity dispersions returned by the MLE routine. We also need to correct the measured dispersions for the measuring errors of the individual PNe, as shown in Fig. 4.3 (see Chapter 4). The rms measuring error in each radial bin is about 6 km s^{-1} . The formal variance of the corrected cold dispersion value at all PNe radial bins is negative. Hence we show its 90% confidence upper limit in Fig. 5.7 and Table 5.4.

We carried out a comprehensive analysis using the colour-magnitude cut to discriminate between the HII regions and PNe. However, removing HII contaminants in disc galaxies is very challenging. There is a small probability that we may still have some HII contaminants in our cold component. However, we do not use the dispersion of our cold component in any further analysis. Our aim is to separate out the cold component (whether cold PNe or HII regions) from the kinematically hot component and then use the $\sigma_{z,hot}$ with the scale height for the same population to calculate the surface mass density. Hence, the nature of the objects that contribute to our cold dispersion is irrelevant as long as they are separated out effectively.

5.5 Results

Fig. 5.7 shows the results obtained from the integrated light VIRUS-W data (points at $R = 54''$ and $98''$) and the planetary nebulae from the PN.S data (3 outer points) in each radial bin. At each radius, we show our one component dispersion, and then the hot and cold thin disc dispersion from our double Gaussian fit.

As mentioned in the previous section, the dispersion values that we obtained from our analysis have been corrected for the small local HI dispersion, which was introduced when we used the HI data to remove galactic rotation, and for the measuring errors for the velocities of individual PNe. The corrections to our hot-component

dispersions are negligible.

The black solid curve in Fig. 5.7 is an exponential with twice the galaxy's scale length in the R-band, see Table 5.2). The scale lengths for this galaxy available from literature cover a large range of values with significant errors. Walsh et al. (2002) provide a table with the different scale length obtained from different photometric studies. We finally decide to adopt the R-band scale length from Larsen & Richtler (1999), $h_R = 80''$. This value is also consistent with $H\alpha$ scale lengths obtained from other studies (Malhotra et al. 1996, Ferguson et al. 1998). In Fig. 5.7, if we allow the fitting routine to find the best scale length for the hot dispersions, it finds a very similar value for the scale length, supporting the adoption of $h_R = 80''$. Thus, we are substantiated in adopting an $h_R = 80''$. Fitting this curve to the data, we find that the central vertical dispersion for the hot component is $\sigma_{z,0} = 87.8 \pm 4.9$ km s $^{-1}$. If we assume a single homogeneous population of tracers, and fit our one component model with an exponential with twice the galaxy's scale length, we find the central vertical dispersion = 57.5 ± 1.1 km s $^{-1}$. Using this dispersion would underestimate the surface mass density by a factor of 2.3.

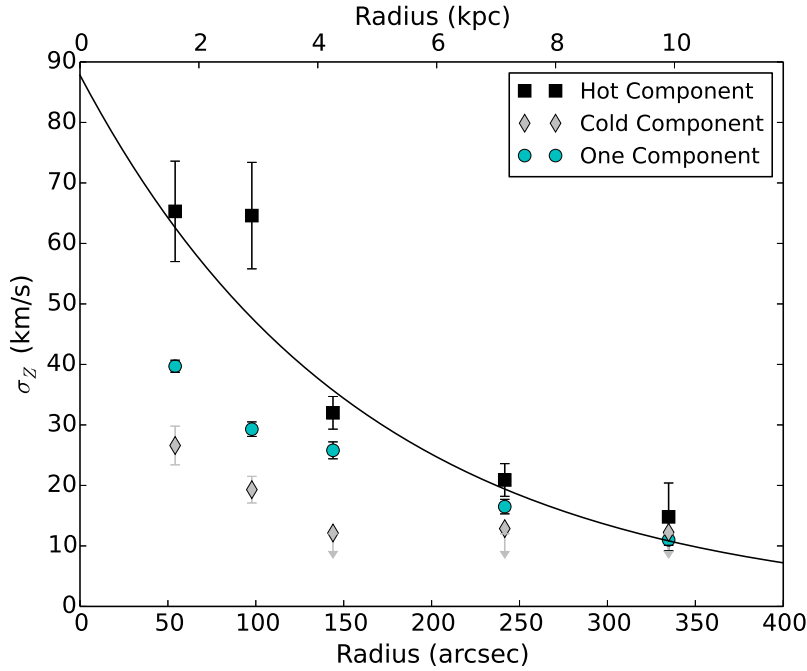


Figure 5.7: The vertical velocity dispersion as a function of radius in NGC 6946. The black and grey markers indicate the hot and cold velocity dispersions respectively from our two component fits, the cyan markers are our single-component values. The two inner data points at $R = 54''$ and $98''$ were obtained for integrated light spectra from VIRUS-W and the outer data points are for PNe from PN.S. The solid line denotes an exponential with twice the galaxy's R-band scale length ($h_R = 80'' = 2.37$ kpc, based on literature value), fit to the hot component. Our data have been corrected for the HI velocity dispersion and PNe measuring errors. The cold component from the PN.S data were dominated by our errors, and we show the 90% upper limits for these values. The errors bars are the 1σ errors obtained from monte carlo simulations.

In Fig. 5.7, we note that the difference between the one component dispersions and our hot component dispersions decreases with radius and is almost zero in the outermost radial bin. This is consistent with our BIC values shown for the outer radial bin, which do not favour the two component model in the outer bin.

Mean Radius (arcsec)	2 component Model			1 Component Model	
	$\sigma_{z,cold}$ (km s ⁻¹)	$\sigma_{z,hot}$ (km s ⁻¹)	BIC	σ_z (km s ⁻¹)	BIC
144	$\leq 12.1 \pm 1.7$	32.0 ± 2.7	1236	26.5 ± 1.7	1251
242	$\leq 12.9 \pm 2.8$	20.9 ± 2.7	1076	18.6 ± 1.2	1090
335	$\leq 12.3 \pm 3.2$	14.8 ± 5.6	1062	14.5 ± 1.0	1055

Table 5.4: The σ_z values calculated from the PN.S data. We give the 90% confidence upper limit for the cold dispersions. The lower BIC values of the two component fit (except in the outermost radial bin) make it the preferred model over the one component model.

5.5.1 Estimating Disc Scale Height

Estimating scale heights for face-on discs is challenging. We can only obtain the scale height from statistical studies of edge-on galaxies in the near-infrared. In the case of NGC 628, we adopted the same scale height as Herrmann & Ciardullo (2009b) to enable a direct comparison of our results with theirs. However, for this galaxy we need to calculate the scale height by using correlations between the scale height and other observable properties of the galaxy, such as its scale length from photometry.

Kregel et al. (2002) studied the scale heights of a sample of edge-on galaxies in the I-band and found strong correlations with the scale lengths. Bershadsky et al. (2010b) fit the Kregel et al. (2002) data and find the relation: $\log(h_R/h_z) = 0.367 \log(h_R/\text{kpc}) + 0.708 \pm 0.095$. Using this relation for NGC 6946, and using an I-band scale length from Larsen & Richtler (1999), we get $h_z = 343 \pm 75$ pc. We will use this value to calculate the surface mass density.

5.5.2 Stellar Surface Mass Density: isothermal model excluding the gravity of the cold component

Using Eqn. 4.1 with $f = 1/2\pi$ (isothermal model), we calculate the surface mass density in each of our radial bins. The results are tabulated in Table 5.5. Calculating the M/L for NGC 6946 proved to be a challenge. Larsen & Richtler (1999) do not provide their surface brightness profiles in their paper. Walsh et al. (2002) used this same data and presented the scale lengths for each band. However, they do not provide values for the central surface brightness, except in the V-band. Therefore, we used the central surface brightnesses from Makarova (1999). They provide BVI surface brightness profiles and their V-band central surface brightness agrees with the value in Walsh et al. (2002). We could not find the surface brightness profile in

the R-band for NGC 6946. Therefore, we only present the M/L in the BVI bands. We used the BVI surface brightness profiles and the foreground extinction correction from Schlafly & Finkbeiner (2011), to calculate the M/L value in each radial bin tabulated in Table 5.5. The M/L value is the ratio of the surface density of the isothermal old thin disc (in $M_\odot$) to the total surface brightness (in $L_\odot$).

Instrument	Mean Radius (arcsec)	Color B - I	σ_z (km s ⁻¹)	Surface Mass Density ($M_\odot$ pc ⁻²)	(M/L) _B	(M/L) _V	(M/L) _I
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VIRUS-W	54	2.7	65.3 ± 8.3	460 ± 152	3.0 ± 1.0	2.9 ± 1.0	1.7 ± 0.6
VIRUS-W	98	2.6	64.6 ± 8.8	450 ± 157	4.7 ± 1.6	4.9 ± 1.7	2.9 ± 1.0
PN.S	144	2.5	32.0 ± 2.7	110 ± 31	1.9 ± 0.5	2.1 ± 0.6	1.2 ± 0.4
PN.S	242	2.4	20.9 ± 2.7	47 ± 16	2.3 ± 0.8	3.1 ± 1.0	1.7 ± 0.6
PN.S	335	2.3	14.8 ± 5.6	24 ± 19	3.3 ± 2.6	4.9 ± 3.9	2.8 ± 2.2

Table 5.5: The results from the calculation of the surface mass density and M/L for a self-gravitating vertically exponential disc. Foreground extinction correction has been applied to the M/L values. The uncertainty in the scale height determination are the largest source of error. The columns are: (1) instrument used for the observations, (2) average radius of the radial bin (the values for the VIRUS-W bins are the luminosity-weighted radius), (3) color based on photometric data from Larsen & Richtler (1999), (4) vertical velocity dispersion of the hot component, (5) calculated surface mass density using the dispersion of the hot component, (6 – 8) M/L corrected for foreground extinction in different bands.

5.5.3 Stellar Surface Mass Density: isothermal model including cold component

Similar to the analysis of NGC 628, we look at the effect of the isothermal cold disc and the cold gas on the calculated M/L (see Appendix B for more details). Column 5 in Table 5.5 measures the total surface mass density of the galaxy, including the hot and cold isothermal layers. The cold layer is further made up of the cold thin disc and the gas in the galaxy. Thus the formula used to calculate the surface mass density derived from the Jean’s equation in the vertical direction (see Eqn. 4.1) actually measures the *total* surface density (young and old): $\sigma_z^2 = 2\pi G h_z \Sigma_T = 2\pi G h_z (\Sigma_C + \Sigma_D)$, where Σ_C is the surface density of the cold layer (gas + cold disc) and Σ_D is the surface mass density of the hot disc. The derived surface density of the old disc is then a bit lower than the values given in Table 5.5.

We obtain the surface mass density of the gas from literature (Crosthwaite & Turner 2007). This galaxy has an unusually large amount of molecular gas in the inner parts. The thin cold layer comprises gas and young stars, which we write as $\Sigma_C = \Sigma_{C,\text{gas}} + \Sigma_{C,*}$ where $\Sigma_{C,\text{gas}}$ is got from Crosthwaite & Turner (2007). The stellar contribution $\Sigma_{C,*}$ is not known directly from our data. In the following section, we estimate the effect of the cold gas layer at the five radii in NGC 6946 (2.6 kpc to 12.2 kpc) where we have velocity dispersion data.

From Eqn. B.10 in the appendix, the velocity dispersion of the isothermal sheet is $\sigma_z^2 = 2\pi G h_z (\Sigma_C + \Sigma_D)$. The adopted scale height $h_z = 343 \pm 75$ pc. Assuming

h_z is constant with radius, the radial variation of σ_z^2 will follow the total surface density rather than the surface density of the isothermal sheet. In NGC 6946, the gas fraction of the total surface density is significant at larger radii (Table 5.6). The scale length for σ_z^2 should then be longer than the photometric scale length. A hint of this effect is seen in the outermost data point in Fig. 5.7.

R (kpc)	σ_z (km s ⁻¹)	Σ_T (M _⊙ pc ⁻²)	$\Sigma_{C,\text{gas}}$ (M _⊙ pc ⁻²)	L_C/L_D	F_C	Σ_D (M _⊙ pc ⁻²)	$\Sigma_{C,*}$ (M _⊙ pc ⁻²)	$(M/L)_V$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1.6	65.3	460	87.7	52/48	0.18	316	57	2.0
2.9	64.6	450	43.0	46/54	0.14	357	50	3.9
4.3	32.0	110	33.3	49/51	0.16	66	11	1.3
7.2	20.9	47	17.5	49/51	0.16	25	4	1.6
9.9	14.8	24	8.6	49/51	0.16	13	2	2.7

Table 5.6: Parameters for NGC 6946 at the five radii where the velocity dispersion of the hot disc was measured (inner two radii from integrated light, outer three from PNe). All surface densities are in units of M_⊙ pc⁻². The columns are (1) radius, (2) vertical velocity dispersion σ_z of the hot disc, (3) total surface density Σ_T from Eqn. B.10 in the appendix, (4) observed surface density $\Sigma_{C,\text{gas}}$ of the gas layer from Crosthwaite & Turner (2007), (5) ratio of luminosities of cold and hot layers from the integrated spectra in rows 1 and 2, and adopting the mean of rows 1 and 2 in rows 3 to 5, (6) the ratio F_C of the stellar surface densities of the cold and hot layers, (7) the surface density Σ_D of the hot layer from Eqns. 5.3, (8) the stellar surface density $\Sigma_{C,*}$ of the cold layer, (9) the $(M/L)_V$ ratio of the hot layer with surface density Σ_D .

The surface densities of the stellar disc components are given by:

$$\Sigma_D = \frac{\Sigma_T - \Sigma_{C,\text{gas}}}{1 + F_C} \quad \text{and} \quad \Sigma_{C,*} = F_C \Sigma_D. \quad (5.3)$$

Assuming NGC 6946 has the same age-velocity relation as in the solar neighbourhood i.e the old thin disc is composed of stars with ages between 3 – 10 Gyr, assuming a star formation rate that decays with time like $\exp(-t/\tau)$ and using stellar population models from Bruzual & Charlot (2003), we find that for $\tau > 3$ Gyr, the M/L ratios for the young and old populations vary with τ almost in lock-step. Therefore, the ratio $F_C = \Sigma_{C,*}/\Sigma_D$ is about 0.12, almost independent of τ . We then compute the ratio of the M/L for the cold stellar component to the M/L of the hot component to be 0.167. The value F_C in Eqn. 5.3 is then = $(L_C/L_H) \times [(M/L)_C/(M/L)_H]$, where L_C and L_H are the luminosity of the cold and hot component respectively and $(M/L)_C$ and $(M/L)_H$ are the mass-to-light ratios of the cold and hot stellar components respectively.

In the first two rows of Table 5.6, we use values of F_C derived from the (cold, hot) component contributions to the integrated light spectrum as described above. In the following rows, where the velocity dispersions come from PNe, we adopt the mean value of 0.16 for F_C from the integrated light spectra. Table 5.6 gives F_C , Σ_D , $\Sigma_{C,*}$ and finally the $(M/L)_V$ ratio for the hot component at each radius.

5.5.4 Rotation Curve Decomposition

We decompose the HI rotation curve in the same way as for NGC 628. The rotation curve was obtained using HI data from the THINGS HI survey (Walter et al. 2008). A velocity field is constructed from the data by fitting a Gauss-Hermite polynomial to the velocity profiles. This velocity field is corrected for the skewness of the profiles, in order to remove non-circular motions, using the technique described in Ponomareva et al. (2016). We then derive the rotation curve from the velocity field by fitting a tilted-ring model (Begeman 1989), using the Groningen Imaging Processing System (Gipsy, van der Hulst et al. 1992).

Using the central surface mass density for the hot component, we fit an exponential disc for the hot component using the scale height adopted for this galaxy. The gas and cold disc component are considered to be isothermal sheets with negligible thickness. The gas radial structure is directly observed (Crosthwaite & Turner 2007). The cold and hot stellar disc are taken to be radially exponential with the same photometrically determined scale length. This approach results in a smooth rotation curve for both the stellar components.

The surface brightness profiles of NGC 6946 indicate the presence of a small bulge component. We, therefore, fit a bulge component as well to the rotation curve using a stellar M/L for $3.6 \mu\text{m} = 0.6$ (Meidt et al. 2012; Querejeta et al. 2015; Röck et al. 2015). We model the bulge assuming a spherical potential. The rotation curves of all the baryonic components were modelled with the same radial sampling as was used for the derivation of the observed rotation curve.

5.5.4.1 Mass modelling

The total rotational velocity of a spiral galaxy can be calculated using the relation:

$$V_{tot}^2 = V_{gas}^2 + V_{\star}^2 + V_{halo}^2, \quad (5.4)$$

where V_{gas} , $V_{\star}$ and V_{halo} are the rotational velocities of the gas (molecular+atomic), the stellar component and the dark halo respectively. We have information on all the baryonic components of the galaxy, namely the hot and cold stellar disc, the total gas and the bulge component. Once we fit all the known rotational velocity from the baryonic components, we can derive the rotation curve of the dark matter halo by fitting various parameters until V_{tot} matches V_{obs} as closely as possible. Since we have measured the dynamical surface mass density of the galaxy, we do not have any of the uncertainties related to M/L that are a major concern in decomposing rotation curves. This allows us to fix the gas and stellar rotation curves and only fit the rotation curve of the dark matter halo. This breaks the disc-halo degeneracy and allows us to test the maximality of the disc directly.

We, again, fit a spherical pISO (pseudo isothermal) and NFW-halo to model the dark halo rotation curve. The pISO halo has a central core and is parameterised by its central density (ρ_0) and the radius of the core (R_c). The NFW halo (Navarro et al. 1997) is parameterised by its mass (M_{200}) within the viral radius (R_{200}) and its concentration (c). We have already explained these dark matter models in Chapter

4 (see Eqn. 4.10 and Eqn. 4.11).

The Gipsy task ROTMAS was again used to find the rotation curves for the dark haloes. The results from this modelling is presented in Fig. 5.8 (the top panel is for the pISO halo and the bottom panel for the NFW halo). The derived parameters of the fitted dark matter rotation curves are presented in Table 5.7. The error on the total rotational velocity (magenta line in Fig. 5.8) follows from the error on the central surface density.

pISO			NFW		
R_C (kpc)	ρ ($10^{-3} \text{ M}_\odot \text{ pc}^{-3}$)	χ_{red}^2	C	R_{200} (kpc)	χ_{red}^2
2.8 ± 0.2	57.6 ± 7.8	0.93	10.8 ± 0.9	169.3 ± 6.5	1.1

Table 5.7: The derived parameters of the fitted dark matter haloes from the mass modelling. Solely based on the value of the χ_{red}^2 , the pISO model may be a better fit to the data.

5.6 Conclusions

We use absorption line spectra in the inner regions and planetary nebulae in the outer regions of the galaxy NGC 6946 to trace the kinematics of the disc. We show that there exists a younger, kinematically colder population of tracers among a more older component.

When attempting to break the disc-(dark halo) degeneracy by measuring the surface mass density of the disc, using the velocity dispersion and the estimated scale height of the disc, it is crucial that the dispersion and the scale height refer to the same population of stars. The scale height, obtained from NIR studies of edge-on galaxies pertains to the older population of thin disc stars. We use this scale height with the dispersion of the hotter component to calculate the surface mass density. This density is a factor of $2.3\times$ greater than the surface density we would get if we assume a single homogeneous population of tracers. This factor is large enough to make the difference between concluding that a disc is maximal or sub-maximal.

We find that the observed vertical velocity dispersion of the hotter component follows an exponential radial decrease, with a scale length of twice the galaxy's photometric scale length. This indicates that the M/L in this galaxy is close to constant over the radial region probed by our study, consistent with the M/L values measured directly. Table 5.5 provides M/L values for the disc of NGC 6946 at several radii and in the BVI photometric bands, excluding the effect of the cold layer to be consistent with previous analyses. We also look at the influence of the cold gas and the cold stellar disc on the surface mass density. Table 5.6 gives the M/L in the V-band after we factor in the gravity of the cold isothermal sheet.

Decomposing the rotation curve of this galaxy, after taking into account the hot and cold stellar components, leads to a clearly maximal disc. The disc contributes

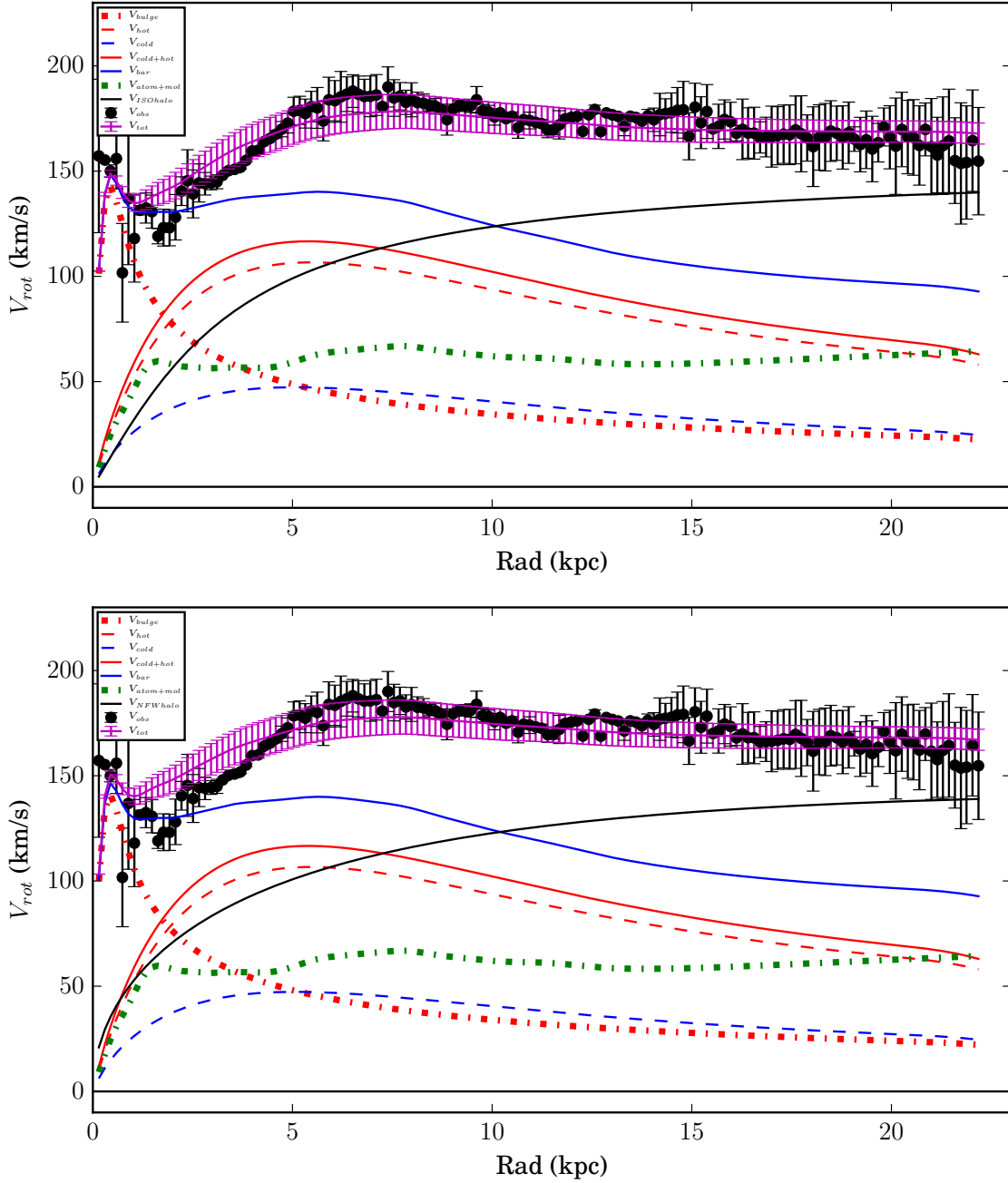


Figure 5.8: The rotation curve decomposition for NGC 6946 by fitting a pISO halo (top panel) and a NFW halo (bottom panel). Observed HI rotation curve is shown as black dots. The rotational velocity of the atomic + molecular gas is shown as the green as the dashed–dotted line. The rotation curve for the bulge is shown by the red dashed–dotted line. The hot and cold stellar disc rotational velocities are indicated using the dashed red and blue curves respectively. The solid red line represents the combined rotation velocity of the two stellar components (hot+cold). The fitted dark matter halo rotation curve is shown by the black solid line. The blue solid curve is the rotation curve from the total baryonic component: bulge+gas+disc. The magenta line represents the total rotational velocity: $V_{tot}^2 = V_{gas}^2 + V_{hot}^2 + V_{cold}^2 + V_{halo}^2$.

about 70% of the rotation curve at its peak ($R \sim 2.2$ scale lengths). The molecular gas makes an unusually large contribution in the inner parts of this galaxy, and the baryons together dominate the radial component of the gravitational field out to a radius of about 10 kpc.

In the next chapter, I analyse the grand design spiral galaxy NGC 5457. NGC 5457 presents some complications, because its rotation curve shows a large disturbance in the approaching part. However, this galaxy was studied by Herrmann & Ciardullo (2009b) and we were keen on a direct comparison with their results. These are discussed in detail in Chapter 6.

NGC 5457

6.1 Introduction

NGC 5457 (M101) is a grand design spiral in the constellation Ursa Major. It is close to face-on with an inclination $\sim 28^\circ$ and is at a distance of $D = 7.3 \pm 0.5$ Mpc (Herrmann & Ciardullo 2009b). This galaxy has negligible foreground extinction. It was also analysed by Herrmann & Ciardullo (2009b) which lets us directly compare our results with theirs.

NGC 5457, however, presents a challenge in terms of rotation curve decomposition. The HI rotation curve on the approaching side of the galaxy shows a large disturbance in terms of the kinematics (see for example Bosma et al. 1981). There are studies that suggest it may be caused by two HI gas clouds that were identified close to the disturbed region (Mihos et al. 2012). This disturbance complicates any attempt to decompose the rotation curve beyond a radius of $400''$.

We observed this galaxy using the VIRUS-W spectrograph as well as the PN.S. In this galaxy, we have significant overlap between the region of the galaxy surveyed by the PNe and the IFU study. This lets us compare the kinematics of the galaxy determined from two separate techniques. This chapter is written following the same structure as Chapter 4 and 5: Section 6.2 describes the observations and data reduction for VIRUS-W, and section 6.3 summarises the same for the PN.S. Section 6.4 details the double Gaussian decomposition to extract the vertical velocity dispersion for the hot and cold components. Section 6.5 describes the calculation of the disc surface mass density, using the dispersion for the hot component and its implications on the rotation curve decomposition, and section 6.6 lists the conclusions from this study for NGC 5457.

6.2 VIRUS-W Spectrograph

6.2.1 Observations

We carried out VIRUS-W observations for NGC 5457 in May 2014. We obtained data in 10 IFU fields – 6 of which were at a radius of $\sim 185''$ and 4 fields at a radius of $\sim 250''$. However, only the inner radial bin gave us good quality data. The fields in the outer radial bin were too faint and we were not able to sky subtract the spectra effectively. Therefore, we only analysed the high quality data from the

inner radial bin at a radius of $\sim 1.3h_R$ for this project. Our IFU positions on the galaxy are shown in Fig. 6.1. The fields were placed along the major and minor axis, as well as two intermediate positions.

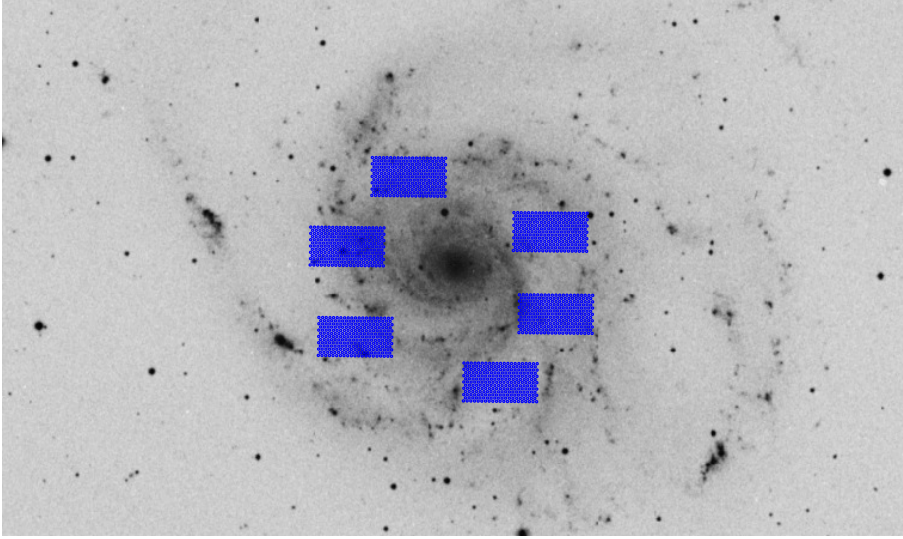


Figure 6.1: The positions of the VIRUS-W IFU fields overlaid on a DSS image of NGC 5457. The position of the 267 fibres in each field are also shown. Only the fields that gave good quality data, which we used for our analysis, are shown.

The position and exposure time at each position is given in Table 6.1. We, again, carried out a sky – galaxy – sky observing sequence and repeated the sequence at least thrice in each field, to help with sky subtraction in these faint sky limited regions of the galaxy.

RA (J2000)	Dec (J2000)	Exposure Time (s)
14:03:24.63	+54:23:38.5	3×625
14:03:04.18	+54:18:45.0	3×625
14:03:02.23	+54:22:06.6	3×625
14:03:26.93	+54:19:34.4	3×625
14:03:03.65	+54:20:25.1	3×625
14:03:37.26	+54:22:01.1	6×625

Table 6.1: Coordinates and exposure times for the IFU fields in NGC 5457.

Unlike NGC 628 and NGC 6946, for this galaxy we did not split our data into two radial bins. We were further out in radii in NGC 5457 compared to other galaxies and had smaller exposure times in each field (due to observing constraints). We would not have enough SNR in each bin if we split the data into two radial bins. Furthermore, this galaxy is very large and our IFU fields cover a shorter radial extent in NGC 5457 compared to other galaxies. Therefore, we decided to sum up the spectrum from each fibre in the six fields to create one high SNR spectrum representative of the kinematics of this galaxy at a radius of about $185''$. We again used the standard CURE reduction pipeline to get the sky subtracted 1D spectrum.

6.3 Planetary Nebula Spectrograph

6.3.1 Observations and Velocity Extraction

The data for NGC 5457 were acquired during a PN.S observing run in April 2015. Since this galaxy is very large, we employed a different observing strategy compared to NGC 628 and NGC 6946. We placed the PN.S on nine different positions around the galaxy. Several images in the [OIII] left and right arms were obtained in each field. Fig. 6.2 shows the positions of these fields on a dss image of the galaxy. Table 6.2 gives the details of the position and exposure times for the [OIII] PN.S images in the various fields.

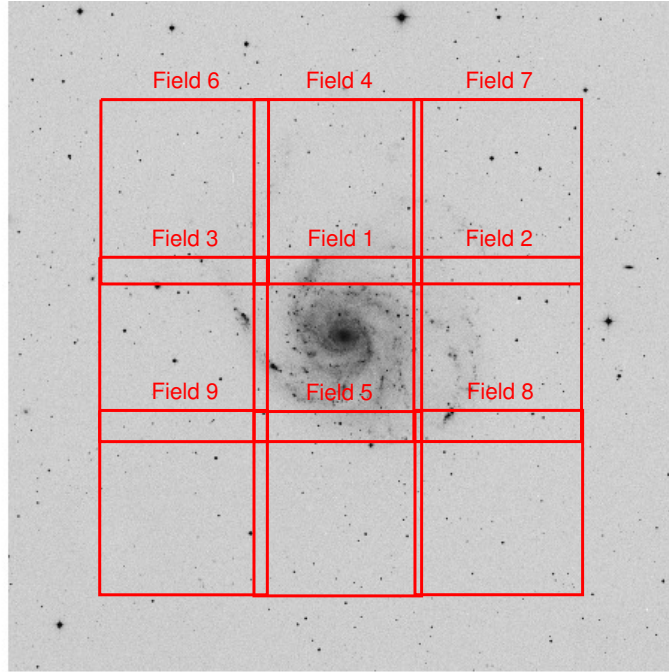


Figure 6.2: The position of the PN.S fields around NGC 5457. Each field is $10' \times 11'$.

	RA (J2000)	Dec (J2000)	Exposure Time (s)
Field 1	14:03:14.67	+54:20:11.5	4×1800
Field 2	14:02:09.23	+54:20:15.5	3×1800
Field 3	14:04:17.81	+54:20:05.6	3×1800
Field 4	14:03:15.21	+54:29:35.9	4×1800
Field 5	14:03:14.15	+54:10:59.2	4×1800
Field 6	14:04:18.13	+54:29:30.0	3×1800
Field 7	14:02:09.52	+54:29:39.9	3×1800
Field 8	14:02:08.50	+54:11:07.2	3×1800
Field 9	14:04:17.06	+54:10:57.2	4×1200

Table 6.2: Coordinates and exposure times for the IFU fields in NGC 5457. These exposure times are for the left and right [OIII] images.

The standard PN.S reduction pipeline (described in Chapter 3) was used to reduce the [OIII] images and then stack these images from the left and right arms in each field. We also observed NGC 5457 in $H\alpha$ in each of the nine fields, using the $H\alpha$ narrow band filter on the undispersed $H\alpha$ arm of the PN.S. We will now use the [OIII] stacked images along with the $H\alpha$ stacked image to identify the PNe candidates in this galaxy.

6.3.2 Identification of Sources

After data reduction, we identified unresolved [OIII] objects in the stacked images from each field. Since the fields have a region of overlap between them, we made sure that a PNe candidate was only included once in our sample. We identified these objects on our $H\alpha$ image as well to discriminate between the HII contaminants. We identified 1633 unresolved objects with both [OIII] and $H\alpha$ emission in this galaxy, out to a radius of $\sim 1000''$. Among our sample of galaxies, this is the most well-sampled galaxy. From the measured positions of these sources on the left and right images, astrometric positions and LOS velocities were derived simultaneously.

We used our spectrophotometric standard stars to convert our instrumental magnitudes to the m_{5007} magnitudes (refer to Eqn. 3.1 from Chapter 3). These magnitudes were corrected for the effects of foreground extinction from Schlafly & Finkbeiner (2011), although for NGC 5457 it is a negligible effect. The bright luminosity cut-off for PNe in this galaxy is expected to be $m_{5007} = 24.61$. Fig. 6.3 shows

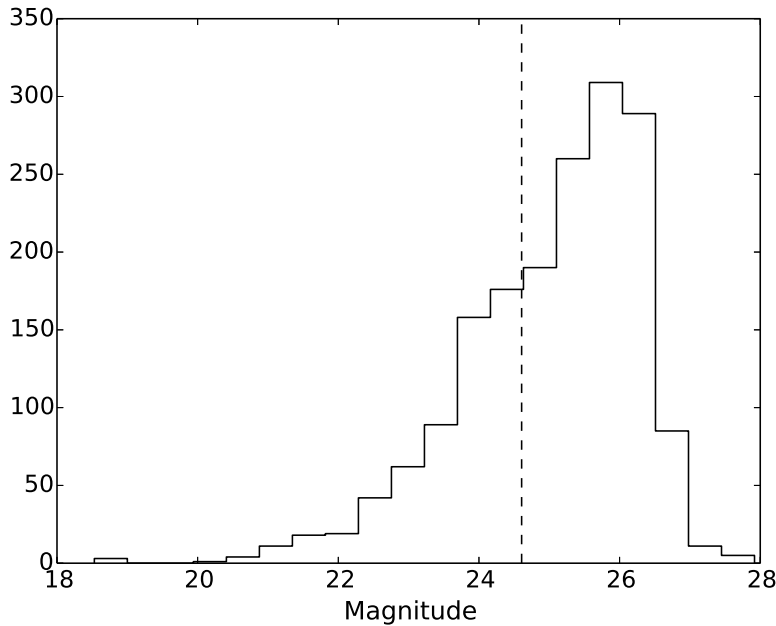


Figure 6.3: The luminosity function for NGC 5457 showing all spatially unresolved [OIII] emitters identified in the combined left and right images of the PN.S. The dashed line shows the expected bright luminosity cut-off for PNe. Objects brighter than the cut-off are likely bright HII regions.

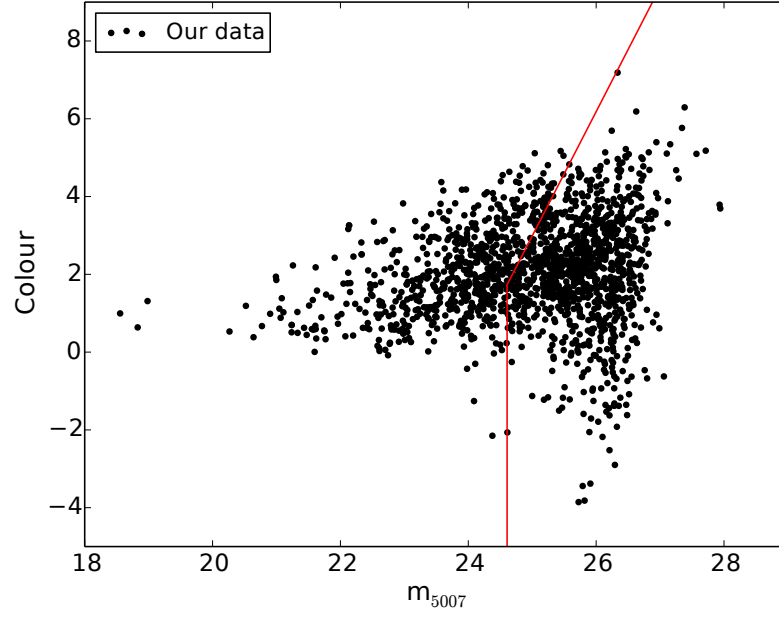


Figure 6.4: The colour-magnitude plot for NGC 5457. The vertical axis is the $[\text{OIII}] - \text{H}\alpha$ colour and the horizontal axis is the m_{5007} magnitude. The PNe lie to the right of the red lines. Only these objects are used in our analysis.

the luminosity function for NGC 5457, including all identified unresolved sources – PNe + HII regions. The dashed line in the plot shows the position of the bright luminosity cut-off for the PNe.

To identify and discard all the [HII] region contaminants in this galaxy, we again use our empirical relationship between the $[\text{OIII}] - \text{H}\alpha$ colour and m_{5007} magnitude (as described in Chapter 3). Fig. 6.4 shows this colour-magnitude plot and our empirical relation to differentiate the true PNe candidates and HII regions.

NGC 5457 has three known historical supernovae according to the IAU Central Bureau for Astronomical Telegram List of Supernovae website (<http://www.cbat.eps.harvard.edu/lists/Supernovae.html>). One of our PNe objects was found at a distance of $\sim 0.9''$ from the supernova SN 1951H. We removed this object from our sample and it was not included in any analysis. Hence, we ensured that we don't have any of these contaminants in our final PNe sample.

Our typical measuring errors as estimated for NGC 628, are found to be $< 9 \text{ km s}^{-1}$ (see section 4.3.3 in Chapter 4).

6.4 Extracting Velocity Dispersions of the Hot and Cold Components

Fig. 6.5 shows the results of the kinematic fit to the HI data from the THINGS survey (Walter et al. 2008) for NGC 5457. The bottom panel shows the rotation curve for this galaxy. The receding side of the galaxy is well behaved, whereas the

approaching side shows a huge disturbance beyond $\sim 400''$. This disturbed part of the galaxy is most likely an infall of a gas cloud (Mihos et al. 2012). Our VIRUS-W data does not go out this far in radius. However, we identified several PNe in the disturbed part of this galaxy. Measuring the kinematics from the PNe in this region will not be representative of the true dynamics of the galaxy. Therefore, we decided to only analyse PN.S data out to $400''$. It's unfortunate that we had to discard very high quality data beyond this radius. We ended up analysing the PNe in three radial bins (with $R < 400''$), each with about 180 objects. We estimated the position angle (PA) from the PNe in each bin. These agree well with the PA obtained from the HI data. The inclination was found to be 28° from the kinematic fit to the THINGS data.

We choose the same distance and scale length adopted by Herrmann & Ciardullo (2009b) for the sake of consistency. Herrmann & Ciardullo (2009b) use the distance to NGC 5457 from Feldmeier et al. (1997) and updated it to be consistent such that the bright luminosity cut-off of the PNe is at an absolute magnitude of -4.47 . (Ciardullo et al. 2002). We adopt the value for scale length from the Koopmann et al. (2006) R band images of NGC 5457. They get an R-band scale length = $140'' = 5$ kpc from their photometric data. Table 6.3 summarises the values that we use for the various parameters required for the double Gaussian decomposition for this galaxy.

Parameters	Value	Source
Scale length (R - band)	$140''$	Koopmann et al. (2006)
Distance	7.3 ± 0.5 Mpc	Herrmann et al. (2008)
Inclination	28°	Kinematic fit to HI data from Walter et al. (2008)

Table 6.3: Adopted parameters for NGC 5457 from literature and used in our analysis.

6.4.1 Stellar Absorption Spectra

6.4.1.1 Removing Galactic Rotation

As in the case of NGC 628 and NGC 6946, we use the THINGS HI data (Walter et al. 2008) to remove the effects of galactic rotation. Since none of our data goes further than $400''$ in radius, which is where the HI kinematics show a large disturbance, we can use the HI data to remove galactic rotation. We subtract the local HI velocity at the position of each fibre which will get rid of any large scale streaming motions across the IFU. Modelling the rotation field and subtracting a smooth rotation curve from our data did not get rid of all the rotation, which was evident from examining the velocity vs. azimuthal angle plots. Hence, we decided that subtracting the local velocity from the THINGS moment 1 map was the best way to get rid of the effects of rotation. Subtracting this component will introduce a small broadening to the velocity dispersion of the apparent stellar velocity dispersion, because the motion of the gas is not purely circular. We will later correct our derived stellar dispersion for this effect.

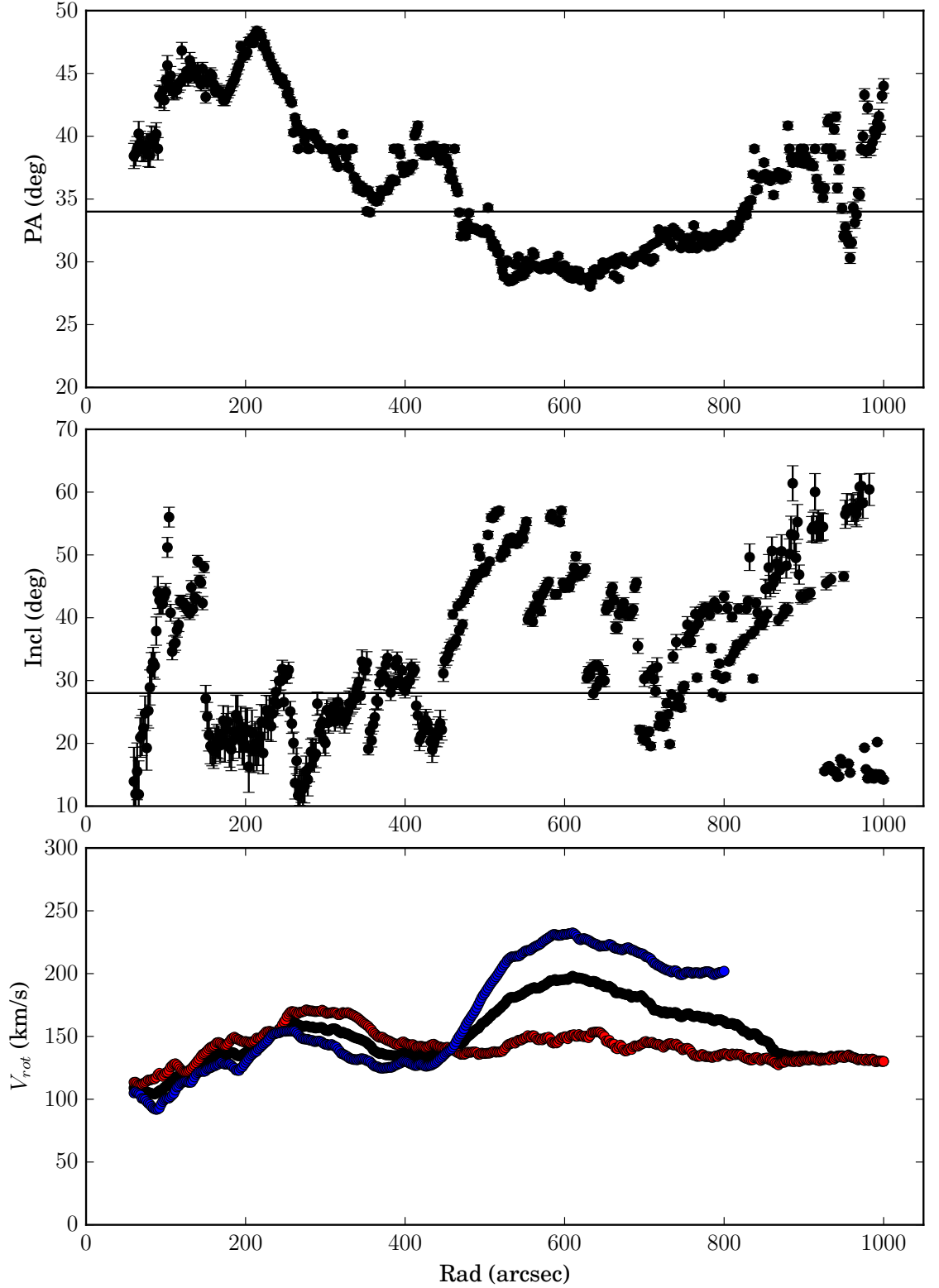


Figure 6.5: Kinematic fits to the HI THINGS data for NGC 5457. The top three panels show the systemic velocity, position angle and inclination as a function of radius. The bottom panel shows the HI rotation curve of the galaxy. The blue and red data points are for the approaching and receding side of the galaxy respectively. The black curve is the average rotation curve for both sides.

NGC 5457 is a very large galaxy and our VIRUS-W fields cover a rather small radial extent on this galaxy. We are also at a distance of 1.3 scale lengths from the centre, with a typically smaller exposure time on each field compared to our previously analysed galaxies. Therefore, in order to maintain a high SNR, we do not split the data into two radial bins as in the case of the previous galaxies. We analyse the data in just the one radial bin, which corresponds to a luminosity-weighted radius of $187''$.

NGC 5457 has an inclination of 28° , which is more face-on than NGC 6946 but considerably more inclined than NGC 628. We will need to correct for differential asymmetric drift in each field, just as we did for NGC 6946, so as to not overestimate the stellar velocity dispersions.. As before, we split the 267 fibres into a grid of six cells, each with about 44 fibres. The gradient in the asymmetric drift is negligible across the small area covered by each cell. We sum the spectra from all fibres in a cell. This gives us 6 spectra, one from each cell. We then cross-correlated five of these spectra against the sixth. That gives us the velocity shifts to apply to the five spectra before summing up all six spectra. This will get rid of any differential asymmetric drift across the IFU fields. We did this on all six of our IFU fields in this galaxy. The cross-correlated, asymmetric drift corrected spectra were then shifted to redshift $z = 0$, before summing up to get the final spectra to analyse. We ended up with a very high quality spectrum with $\text{SNR} \sim 130$ per wavelength pixel. We will now analyse this spectrum to derive the kinematics of the cold and hot components at this position.

We looked for the presence of a thick disc in this galaxy by trying to fit a three Gaussian model to the spectrum – representing the cold thin disc, hot thin disc, and the thick disc. However, we were not able to fit a third component at all to our data. Our pixel fitting code would usually return junk values for the third component, and our information criterion preferred the two component fit. We, therefore, conclude that there is no significant thick disc component that shows up in our data at this radial bin.

We use the direct pixel fitting code pPXF (Cappellari & Emsellem 2004) to look at the high resolution Mgb region of our spectrum to extract the dispersions of the hot and cold components. We had two residual sky lines appearing in one of our fields at $\sim 5200 \text{ \AA}$. When we summed up the spectra from all the fields, this sky line ended up in our final spectrum as well. The two weak [NI] lines in our spectrum (only one of these can be seen clearly in Fig. 6.6) are part of the ISM of the galaxy as they appear at the redshift of the galaxy. The two stronger [NI] lines that overlap them are residual sky lines. This region will be masked out from our analysis anyway, since we get our kinematics from the absorption lines. We are confident that the sky subtraction has worked very well for the galaxy continuum because if not, we would see other sky lines that are at a different redshift to the redshift of the galaxy. Since the emission line region are omitted from the analysis, having these sky lines in the spectrum does not affect our results.

6.4.1.2 LOSVD and the Vertical Velocity Dispersion

We again used pPXF to fit a double Gaussian component to the spectrum. We also fit a single Gaussian component to compare results. We fit the first two moments of the line-of-sight velocity distribution. Table 6.4 tabulates the mean line-of-sight velocity and the σ_{LOS} for the hot and cold component as returned by pPXF. We also tabulate the σ_{LOS} got from the single Gaussian fit for comparison. The Bayesian Information Criterion (BIC; Schwarz 1978) was used to judge the preferred model for the spectra (see Eqn. 4.2 and Eqn. 4.3 in Chapter 4 on how to calculate BIC).

The BIC applies a penalty for models with a large number of fitted parameters. Thus, between 2 models, the model with the lower BIC value is preferred. The one Gaussian and two Gaussian fit results are tabulated in Table 6.4. The two component fit has a lower BIC and is therefore the preferred model.

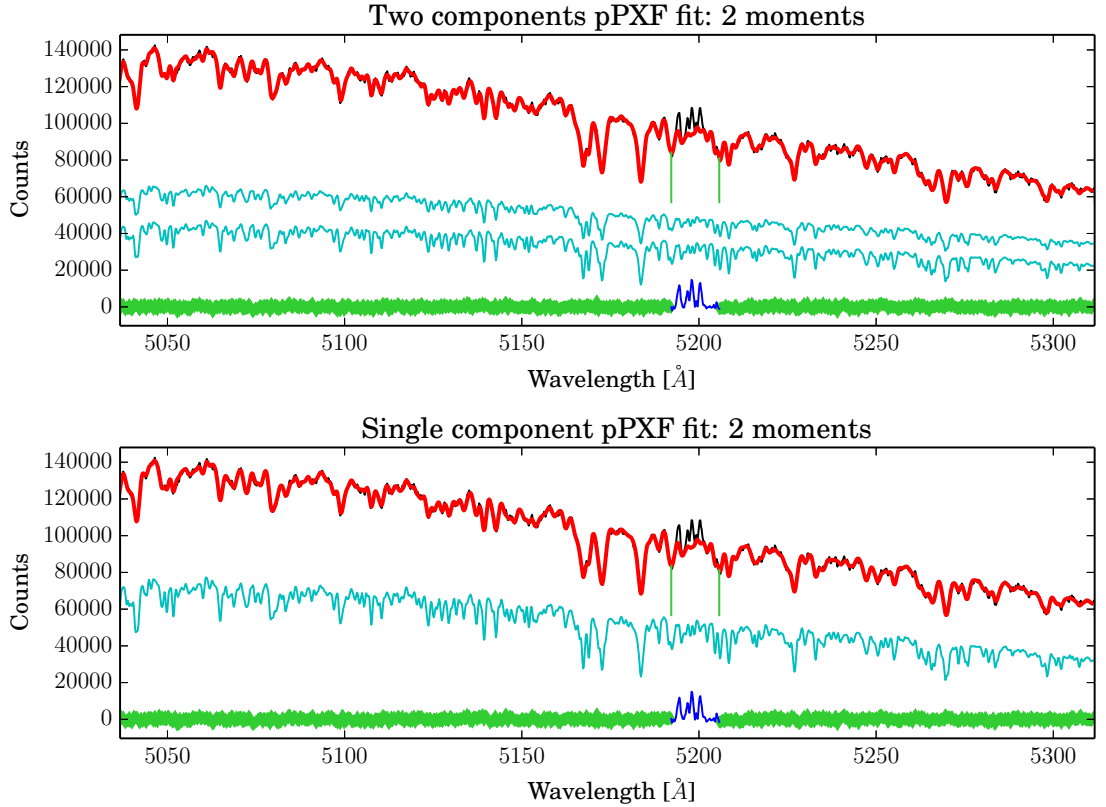


Figure 6.6: The pPXF fit results for NGC 5457. The spectrum is representative of the kinematics of the galaxy at a radius of $187''$. The upper panel shows the double Gaussian fit to the data whereas the lower panel shows a single Gaussian fit. Only the high resolution Mgb region of the spectrum was used for the fit. The galaxy spectrum is in black and is overplotted with the best fit from pPXF in red. The cyan spectra are the two and one component spectra that pPXF found. The cyan spectra have been shifted vertically so as to be clearly visible. The residuals are shown in green. The [NI] doublet emission lines at ~ 5200 Å have been omitted from the fit.

Fig. 6.6 shows the best fit found by pPXF. The two components found by pPXF are plotted in cyan. These are consistent with being spectra from red giants. We find that the cold and hot component contribute 43% and 57% respectively to the total light in this radial bin.

As mentioned earlier, we remove rotation across the IFU fields by subtracting the local HI velocity from THINGS. However, this adds a small broadening to our spectrum due to the fact that the gas does not have purely circular motion. We will need to correct our dispersions (as returned by pPXF) for this small effect. This scatter was determined to be very small $\sim 2.2 \text{ km s}^{-1}$, very similar to the scatter we found for NGC 628.

The errors given in Table 6.4 are the 1σ errors obtained from monte carlo simulations. As explained in previous chapters, this was determined running 1000 iterations where, in each iteration, random Gaussian noise appropriate to the observed SNR of the spectrum was added to the best fit spectrum originally returned by pPXF. pPXF was run again on the new spectrum produced in each iteration. The errors are the standard deviations of the distribution of values obtained over 1000 iterations.

The vertical velocity dispersion (σ_z) can be determined from the σ_{LOS} by breaking down the LOS dispersion into its three orthogonal components:

$$\sigma_{LOS}^2 = \sigma_\theta^2 \cos^2 \theta \cdot \sin^2 i + \sigma_R^2 \sin^2 \theta \cdot \sin^2 i + \sigma_z^2 \cos^2 i + \sigma_{meas}^2 \quad (6.1)$$

In the above equation, σ_R , σ_θ and σ_z are the three components of the dispersion in the radial, azimuthal and vertical direction, and σ_{meas} are the measurement errors on the velocity and i is the inclination of the galaxy ($i = 0$ is face-on). All of our data for NGC 5457 can be considered to lie on a part of the rotation curve that is close to solid body. For this region, we can make use of the epicyclic approximation and adopt $\sigma_R = \sigma_\theta$. We also adopt the σ_R/σ_z ratio to be 1.7, which is consistent with the value used by Bershadsky et al. (2010b) and the value found in the solar neighbourhood. Eqn. 6.1 then reduces to just one unknown: σ_z .

We make sure to correct the σ_z values for the small broadening introduced by subtracting the local HI velocity to remove galactic rotation. Our results for the stellar σ_z for the cold and hot thin disc are shown in Table 6.4. The errors are the 1σ errors from monte carlo simulations.

Mean Radius (arcsec)	2 Component model				1 Component model		
	$\sigma_{z,cold}$ (km s ⁻¹)	$\sigma_{z,hot}$ (km s ⁻¹)	BIC	χ^2_{red}	σ_z (km s ⁻¹)	BIC	χ^2_{red}
187	15.0 ± 0.9	44.3 ± 3.4	18988	1.58	23.2 ± 0.4	19144	1.79

Table 6.4: The single and double Gaussian fit from pPXF. We quote the LOS dispersions and the vertical velocity dispersions derived from them for each component. Dispersions have been corrected for the contribution from the HI velocity dispersion. An estimate of the reduced χ^2 and the Bayesian Information Criterion parameter BIC is also given. The BIC clearly prefers the two component model.

6.4.2 Planetary Nebulae

6.4.2.1 Removing Galactic Rotation

We remove the effects of galactic rotation from our sample of PNe by subtracting the local HI velocity from the moment 1 maps of the THINGS survey (Walter et al. 2008) from the measured radial velocity of the PNe. As discussed in the previous section, the small additional broadening that this adds to our data will be corrected for later.

These velocities, corrected for the rotation are henceforth denoted as v_{LOS} . We will use these velocities in our analysis to determine the vertical velocity dispersion of the hot and cold disc components. We convert the radius and azimuthal angles in the plane of the sky to the values in the plane of the galaxy using our estimated values of PA and inclination. As discussed before, we will only use PNe out to a radius of $400''$ to avoid the disturbed region of the galaxy. We have ~ 540 objects, which we divide into three radial bins, each with about 180 PNe. Fig. 6.7 shows the v_{LOS} as a function of azimuthal angle plots in each radial bin before and after the HI velocities were subtracted off.

6.4.2.2 LOSVD and the Vertical Velocity Dispersion

In each radial bin, we remove a few obvious outliers, based on a visual inspection of the velocity histogram of the objects in each bin. These outliers could be halo PNe or thick disc objects, and should be removed from our sample. Only a small number of objects were removed from each radial bin. As with the previous galaxies, we use our maximum likelihood estimator (MLE) code to calculate the σ_{LOS} and the subsequent σ_z in each radial bin.

The maximum likelihood routine uses Eqn. 4.5 described in Chapter 4 to estimate the σ_{LOS} for the two thin disc components. Once these values are estimated, they are then used as initial guesses in the second iteration of the code to calculate the vertical velocity dispersions of the two components. We have already discussed all the equations involved in deriving the σ_z parameters for the hot and cold components in Chapter 4 and Chapter 5. However, we briefly mention it again as a reminder.

The σ_z is estimated by using the epicyclic approximation that gives $\sigma_R = \sigma_\theta$ for the region where the rotation curve is close to solid body (which is an appropriate assumption for all our radial bins). Just as for the IFU data, we assume $f = \sigma_R/\sigma_z = 1.7$ (Bershady et al. 2010b) and use inclination $i = 28^\circ$ as explained in Table 6.3.

The routine then proceeds to calculate the expected σ_{LOS} for the hot and cold component at each azimuthal angle (θ), based on the initial guesses that were passed to it, using the relation:

$$\begin{aligned}\sigma_{LOS1}^2 &= \frac{\sigma_{z1}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z1}^2 \cos^2 i \\ \sigma_{LOS2}^2 &= \frac{\sigma_{z2}^2 f^2}{2} \cos^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 f^2 \sin^2 \theta \cdot \sin^2 i + \sigma_{z2}^2 \cos^2 i\end{aligned}$$

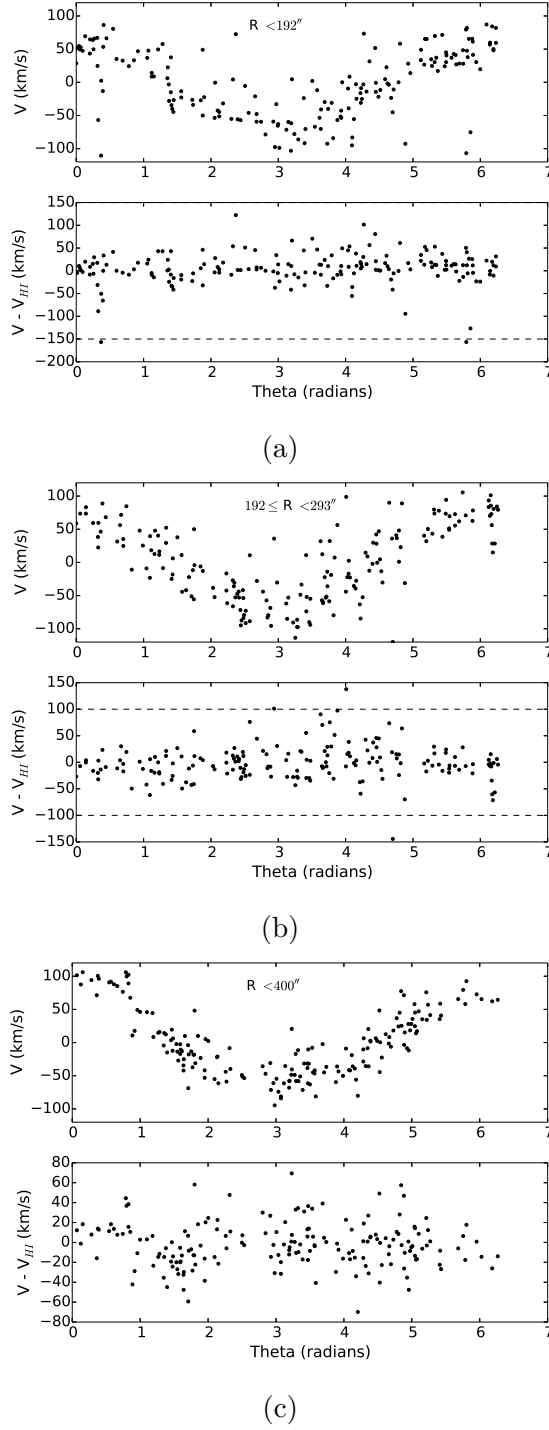


Figure 6.7: Velocity vs azimuthal angle plots in 3 radial bins, each with about 180 PNe. The azimuthal angle θ is in the plane of the galaxy. The top panels show the velocity before taking off the local THINGS velocity and the bottom panels show the velocities after correcting for galactic rotation. A few outliers were removed based on a visual inspection of the velocity histogram of the objects in each bin. The objects within the dashed lines are the ones that were included in our sample for analysis; no objects were thrown out in the third bin. Each panel shows a mix of cold population of spatially unresolved emission line objects, plus a hotter population whose velocity dispersion appears to decrease with galactic radius.

The subscript 1 and 2 refers to the components of the kinematically cold and hot populations respectively. We then calculate the probability of a particular v_{LOS} to be present at that azimuthal angle via the analytic equation:

$$P = \frac{N}{\sigma_{LOS1}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_1 \cos\theta \cdot \sin i)^2}{2\sigma_{LOS1}^2}\right) + \frac{1-N}{\sigma_{LOS2}\sqrt{2\pi}} \exp\left(\frac{-(v_{LOS} - \mu_2 \cos\theta \cdot \sin i)^2}{2\sigma_{LOS2}^2}\right) \quad (6.2)$$

In Eqn. 6.2, N is the value of the fraction of the cold population returned by the routine that calculated σ_{LOS} described earlier. μ_1 and μ_2 are associated with the means of the two components. The $\cos\theta \cdot \sin i$ term factors for any asymmetric drift present in the data by allowing the mean to vary azimuthally. We allowed the code to return the best parameters for N , μ_1 , μ_2 , σ_{LOS1} , and σ_{LOS2} such that the distribution described in Eqn. 6.2 is maximised. The 1σ errors are calculated similar to the method used in the analysis of the VIRUS-W data. We used the double Gaussian distribution found by our MLE code, to pull out about 180 random velocities (i.e same number of objects as in each of our bins). This sample was then used to determine the σ_z again. We repeated this process 1000 times and looked at the distribution of all the σ_z found in each iteration. Our quoted errors are the dispersions of these σ_z distributions.

The vertical velocity dispersions for the two components in each radial bin of NGC 5457 are given in Table 6.5. Fig. 6.8 shows the vertical velocity dispersions determined in each radial bin for both the IFU and PN.S data. Also plotted are the σ_z obtained from fitting a single Gaussian to our data, assuming a single homogeneous population of tracers. Herrmann & Ciardullo (2009b) results for this galaxy are also plotted for comparison. Herrmann & Ciardullo (2009b) find an almost constant σ_z as a function of radius. One reason for this could be that their data go out to a radius $\sim 500''$, which covers the very disturbed part of the galaxy. The kinematics derived in bins beyond $400''$ will not be representative of the true kinematics of the galaxy. As they point out, they have four radial bins with only 15 PNe each and, with such a limited sample, their analysis is susceptible to the effects of disc substructure. They also note that if some of the PNe targeted in this galaxy actually belong to the remnants of a disrupted companion galaxy, then their derived disc mass measurements would be in error (Herrmann & Ciardullo 2009b).

Similar to the VIRUS-W analysis, we correct the dispersions from the PNe for the small broadening ($\sim 2.2 \text{ km s}^{-1}$) introduced by subtracting the HI velocities. We also correct our measured dispersions for the measuring errors of the individual PNe, as shown in Fig. 4.3 (see Chapter 4). The rms measuring error in each radial bin is about 5 km s^{-1} . The values of dispersions quoted in Table 6.5 and Fig. 6.8 are the values after correcting for the errors.

6.5 Results

Our results from the double Gaussian fit are plotted in Fig. 6.8. The vertical velocity dispersions of the hot component are shown as black squares, and the cold dispersions are plotted as grey diamonds. The second data point at a radius of $187''$ are the results from the VIRUS-W absorption spectrum. The other three points are the dispersions from the PNe analysis. At each radius, we also show (in cyan) the dispersions from a one component fit to the data.

As mentioned in the previous section, all the dispersion values have been corrected for the small local HI dispersion, as well as for the measuring errors. The corrections to the dispersions for this galaxy are negligible.

The black solid curve in Fig. 6.8 is an exponential with twice the galaxy's scale length in the R-band (R-band scale length obtained from Koopmann et al. 2006). The adopted scale length $h_R = 140''$ agrees well with the value that we obtain when we fit the dispersion of the hot component with an exponential function. We find that the central vertical dispersion for the hot component in NGC 5457 is $\sigma_{z,0} = 83.2 \pm 5.7 \text{ km s}^{-1}$. Herrmann & Ciardullo (2009b) find a central vertical velocity dispersion $= 38_{-4}^{+8} \text{ km s}^{-1}$ for their data. If we were to fit our one component dispersions with an exponential function, allowing the code to find the best fitting central dispersion and scale length, we get a central dispersion value $= 30.4 \pm 2 \text{ km s}^{-1}$. This agrees quite well with the central dispersion got by Herrmann & Ciardullo (2009b), within errors.

In Fig. 6.8, we note that the difference between the one component dispersions and our hot component dispersions decreases with radius and is almost zero in the last two radial bins. The BIC values quoted in Table 6.5 seem to prefer the one component model in the last two radial bins. However, we note that the difference in the BIC values in the penultimate radial bin ($R = 245''$) is only 2. With such a low difference in the information criteria, we cannot positively rule out the two component model. In this galaxy, when we carried out our double Gaussian decomposition, a large number of objects were classified as the cold component (the parameter N in Eqn. 6.2). The fraction of cold component was much higher compared to the other galaxies that we analysed. This fraction is important when we use monte-carlo simulations to estimate the error on our dispersions (as explained in Section 6.4.2.2). This explains why our errors on the hot component from the PNe analysis are higher than those from the other galaxies; it is representative of the small fraction of objects that are considered 'hot PNe' by our monte carlo code. However, this is the best we can do with 185 objects in each bin. We were limited in sample size when we decided to only retain objects within a radius of $400''$ to avoid the disturbed HI regions of the galaxy. We also note that there is a small chance in the cold PNe being HII contaminants, despite our best efforts in getting rid of them. However, as noted in the previous chapter, we will only be using the hot dispersions for the calculation of the surface mass density. The nature of the 'cold PNe' are irrelevant as our aim is to simply separate them out and then discard them.

Even with the rather large errors on the hot dispersion from the PNe, these dispersions follow an exponential with twice our adopted radial scale length remark-

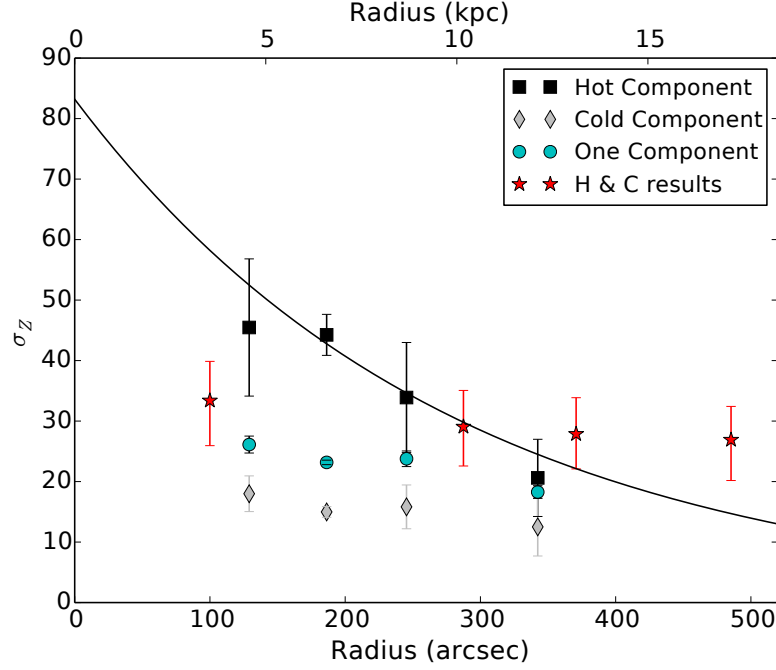


Figure 6.8: The vertical velocity dispersion as a function of radius in NGC 5457. The black and grey markers indicate the hot and cold velocity dispersions respectively from our two component fits and the cyan markers are our single Gaussian fit results. The data points at $R = 187''$ corresponds to the VIRUS-W IFU data, the rest of the points are the results of the analysis from PN.S data. The solid line denotes an exponential with twice the galaxy's R-band scale length ($h_R = 140'' = 5$ kpc, based on literature value), fit to the hot component. Our data have been corrected for the HI velocity dispersion and PNe measuring errors. The errors bars are the 1σ errors obtained from monte carlo simulations.

ably well. There are regions of overlap between the PNe and our IFU fields. The kinematics obtained from these two independent methods agree with each other, as shown in Fig. 6.8.

Mean Radius (arcsec)	2 component Model			1 Component Model	
	$\sigma_{z,cold}$ (km s ⁻¹)	$\sigma_{z,hot}$ (km s ⁻¹)	BIC	σ_z (km s ⁻¹)	BIC
129	18.0 ± 3.0	45.5 ± 11.3	1707	26.1 ± 1.4	1718
245	15.8 ± 3.6	33.9 ± 9.1	1697	23.8 ± 1.3	1695
342	12.5 ± 4.8	20.6 ± 6.4	1644	18.3 ± 1.1	1634

Table 6.5: The σ_z values calculated from the PN.S data for the hot and cold component, as well as for the one component. The BIC value in each radial bin quoted as well.

6.5.1 Disc Scale Height

NGC 5457 was analysed by Herrmann & Ciardullo (2009b) and, for ease of comparison, we adopt their scale height: $h_z = 600 \pm 120$ pc.

This agrees well with the value 543 ± 119 pc, which is the h_z we would get if we used the relation: $\log(h_R/h_z) = 0.367 \log(h_R/\text{kpc}) + 0.708 \pm 0.095$, obtained by Bershadsky et al. (2010b) to their fit to the Kregel et al. (2002) data of edge-on galaxies.

In all further analysis, we will use $h_z = 600 \pm 120$ pc, consistent with the Herrmann & Ciardullo (2009b) study.

6.5.2 Stellar Surface Mass Density: isothermal model excluding the gravity of the cold component

We now proceed to calculate the surface mass density using Eqn. 4.1 from Chapter 4. We adopt $f = 1/2\pi$ (isothermal model) as for all the previous galaxies. We present the calculated surface mass density in each radial bin in Table 6.6. We use the BVI surface brightness profiles from Kuchinski et al. (2000) to calculate the M/L in these bands. The M/L have been corrected for foreground extinction based on Schlafly & Finkbeiner (2011) dust maps. However, foreground extinction is negligible for this galaxy. Herrmann & Ciardullo (2009b) use an R-band central surface brightness of 20.29 mag arcsec $^{-2}$ to calculate their central $(M/L)_R$. We use this same value along with the R-band scale length from Koopmann et al. (2006) to calculate the M/L in the R-band for all our radial bins. The M/L value quoted in Table 6.6 is the ratio of the surface density of the isothermal old thin disc (in $M_\odot$) to the total surface brightness (in $L_\odot$).

Instrument	Mean Radius (arcsec)	Color B - I	σ_z (km s $^{-1}$)	Surface Mass Density ($M_\odot$ pc $^{-2}$)	$(M/L)_B$	$(M/L)_V$	$(M/L)_R$	$(M/L)_I$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
PN.S	129	1.6	45.5 ± 11.3	128 ± 68	1.9 ± 1.0	1.9 ± 1.0	1.6 ± 0.8	1.5 ± 0.8
VIRUS-W	187	1.5	44.3 ± 3.4	121 ± 31	2.6 ± 0.7	2.7 ± 0.7	2.3 ± 0.6	2.3 ± 0.6
PN.S	245	1.3	33.9 ± 9.1	71 ± 41	2.1 ± 1.2	2.4 ± 1.4	2.0 ± 1.2	2.2 ± 1.3
PN.S	342	1.1	20.6 ± 6.4	26 ± 17	1.4 ± 0.9	1.8 ± 1.2	1.5 ± 1.0	1.8 ± 1.2

Table 6.6: The results from the calculation of the surface mass density and M/L for a self-gravitating vertically exponential disc. The columns are: (1) instrument used for the observations, (2) average radius of the radial bin (the values for the VIRUS-W bins are the luminosity-weighted radius), (3) color based on photometric data from Kuchinski et al. (2000), (4) vertical velocity dispersion of the hot component, (5) calculated surface mass density using the dispersion of the hot component, (6 – 9) M/L corrected for foreground extinction in different bands.

Using our central vertical velocity dispersion of the hot component, gives us a central surface mass density $\Sigma(0) = 427 \pm 104 M_\odot \text{ pc}^{-2}$, compared to the value of $100^{+50}_{-20} M_\odot \text{ pc}^{-2}$ from Herrmann & Ciardullo (2009b). We get a central $(M/L)_R = 2.1 \pm 0.5$, whereas Herrmann & Ciardullo (2009b) found a central $(M/L)_R = 0.6 \pm 0.3$. We note that we adopt an isothermal model and use $f = 1/2\pi$, whereas Herrmann & Ciardullo (2009b) use the intermediate model with $f = 1.7051\pi$. This

contributes minimally to the differences in the surface mass density and M/L ; the main contributor is the vertical velocity dispersions used.

6.5.3 Stellar Surface Mass Density: isothermal model including cold component

We look at the effect of the cold isothermal sheet of stars and gas on the M/L presented in Table 6.6. Column 5 in Table 6.6 measures the total surface mass density of the galaxy, including the hot and cold (which includes the cold thin stellar disc and the total gas) isothermal layers in the galaxy. The formula used to calculate the surface mass density derived from the Jean's equation in the vertical direction (see Eqn. 4.1) actually measures the *total* surface density (young and old): $\sigma_z^2 = 2\pi Gh_z \Sigma_T = 2\pi Gh_z (\Sigma_C + \Sigma_D)$, where Σ_C is the surface density of the cold layer (gas + cold disc) and Σ_D is the surface mass density of the hot disc. The derived surface density of the old disc is then a bit lower than the values given in Table 6.6.

The surface mass density of the hot and cold stellar disc is calculated using the relation:

$$\Sigma_D = \frac{\Sigma_T - \Sigma_{C,\text{gas}}}{1 + F_C} \quad \text{and} \quad \Sigma_{C,*} = F_C \Sigma_D. \quad (6.3)$$

where Σ_T is the total baryonic surface mass density (column 5 in Table 6.6), Σ_D and $\Sigma_{C,*}$ are the surface mass densities of the hot and cold stellar disc respectively, and $\Sigma_{C,\text{gas}}$ is the surface mass density of the total gas (atomic + molecular) in the galaxy. The factor $F_C = (L_C/L_H) \times [(M/L)_C/(M/L)_H]$, where L_C and L_H are the luminosity of the cold and hot component respectively and $(M/L)_C$ and $(M/L)_H$ are the mass-to-light ratios of the cold and hot stellar components respectively (see Chapter 4 and Appendix B for details).

We use the surface mass density of the total gas in this galaxy from Kenney et al. (1991), and calculate Σ_D and $\Sigma_{C,*}$ in each radial bin for NGC 5457. The results are presented in Table 6.7.

We use the ratio of luminosity of the cold component to the luminosity of the hot component as being 43/57. This is the value found for the cold and hot component for the VIRUS-W data. We adopt this same value for all bins, because we worry that the cold component found in the PNe bins are a mixture of cold PNe and HII regions. Therefore, we use $F_C = 0.126$ in all bins.

6.5.4 Rotation Curve Decomposition

The rotation curve decomposition for this galaxy was carried out similarly to those of the two previous galaxies. Typically, the HI rotation curve of a galaxy is obtained by averaging the rotation curve of the approaching and receding side of the galaxy. However, since NGC 5457 has a very disturbed kinematics (see bottom panel of Fig. 6.5) on the approaching side, we only use the rotation curve of the receding side for our decomposition. This rotation curve is representative of the underlying 'true' rotation of the galaxy.

R (kpc)	σ_z (km s ⁻¹)	Σ_T (M _⊙ pc ⁻²)	$\Sigma_{C, \text{gas}}$ (M _⊙ pc ⁻²)	L_C/L_D	F_C	Σ_D (M _⊙ pc ⁻²)	$\Sigma_{C,*}$ (M _⊙ pc ⁻²)	$(M/L)_V$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
4.6	45.5	128	28	43/57	0.126	89	11	1.3
6.6	44.3	121	20.8	43/57	0.126	89	11	2.0
8.7	33.9	71	17.8	43/57	0.126	47	6	1.6
12.1	20.6	26	9.4	43/57	0.126	15	2	1.1

Table 6.7: Parameters for NGC 5457 at the four radii where the velocity dispersion of the hot disc was measured (second radial bin from radii integrated light, rest from PNe). All surface densities are in units of M_⊙ pc⁻². The columns are (1) radius, (2) vertical velocity dispersion σ_z of the hot disc, (3) total surface density Σ_T from Eqn. B.10 in Appendix B, (4) observed surface density $\Sigma_{C, \text{gas}}$ of the gas layer from Kenney et al. (1991), (5) ratio of luminosities of cold and hot layers from the integrated spectra in row 2 (6) the ratio F_C of the stellar surface densities of the cold and hot layers, (7) the surface density Σ_D of the hot layer from Eqns. 6.3, (8) the stellar surface density $\Sigma_{C,*}$ of the cold layer, (9) the $(M/L)_V$ ratio of the hot layer with surface density Σ_D .

Using the central surface mass density for the hot component, we fit an exponential disc for the hot component using the scale height adopted for this galaxy. The gas and cold disc component are considered to be isothermal sheets with negligible thickness. This approach results in a smooth rotation curve for all the components.

The brightness profiles and the velocity curve indicated the presence of a small bulge in NGC 5457. We fit this component by assuming the M/L in the 3.6 μ m band to be 0.6 (Meidt et al. 2012) and by assuming a spherical potential. The rotation curves of all the baryonic components were modelled with the same sampling as was used for the derivation of the observed rotation curve.

6.5.4.1 Mass modelling

A galaxy's total rotational velocity can be derived from the rotation curve contributions of each of the gas, stellar disc, and dark halo:

$$V_{\text{tot}}^2 = V_{\text{gas}}^2 + V_{\star}^2 + V_{\text{halo}}^2, \quad (6.4)$$

where V_{gas} , $V_{\star}$ and V_{halo} are the rotation curve contributions of the gas (molecular+atomic), the stellar component (cold+hot component) and the dark halo respectively. We have observationally determined the surface mass densities of the two stellar disc components, and we have the surface mass density of the gas from literature. We can now use this information to determine the contribution of the total baryonic matter to the rotation curve of the galaxy. The contribution of the dark halo can then be determined as: $V_{\text{halo}}^2 = V_{\text{tot}}^2 - V_{\text{baryonic}}^2$.

We, again, fit a spherical pISO (pseudo isothermal) and NFW-halo to derive the parameters of the dark halo (refer to Eqn. 4.10 and Eqn. 4.11 in Chapter 4). The parameters of the best fitting halo that we obtain are tabulated in Table 6.8.

The results from the rotation curve decomposition are shown in Fig. 6.9 (the

top panel is for the pISO halo and the bottom panel for the NFW halo). The error on the total rotational velocity (magenta line in Fig. 6.9) follows from the error on the central surface density.

pISO			NFW		
R_C (kpc)	ρ ($10^{-3} \text{ M}_{\odot} \text{ pc}^{-3}$)	χ_{red}^2	C	R_{200} (kpc)	χ_{red}^2
8.5 ± 1.1	2.4 ± 0.4	1.03	0.5 ± 0.9	280 ± 188	1.10

Table 6.8: The derived parameters of the fitted dark matter haloes from the mass modelling. Solely based on the value of the χ_{red}^2 , the pISO model may be better fit to the data.

6.6 Conclusions

NGC 5457 is a nearby, face-on grand design spiral. We use two complementary analyses – absorption line spectra and PNe to trace the kinematics of the disc. We limit our analysis within a radius of $400''$ despite having data that extends out much further, due to the fact that the HI kinematics of this galaxy shows a large disturbance on the approaching side of the rotation curve beyond $400''$.

We find evidence of a kinematically cold component amongst a population of kinematically hot tracers with much larger dispersions. The vertical velocity dispersion of the hot component declines radially with twice the galaxy’s scale length. The results from the PNe analysis are consistent with the results from the integrated light work.

We use the vertical velocity dispersions of the hot component along with a literature value for the scale height (that refers to these same hotter stars) to calculate the surface mass density at each radial bin. We then use available photometry in the BVRI bands to estimate the M/L in each radial bin. We find that our central surface mass density obtained from the hot dispersions is a factor of ~ 4 times larger than the value got by Herrmann & Ciardullo (2009b) who assumed a single kinematically homogeneous population of PNe in the disc. This difference is significant enough to classify this galaxy as being maximal.

We also look at the influence of the cold gas and the cold stellar disc on the surface mass density. We calculate the M/L in the V-band for each radial bin after we factor in the gravity of the cold isothermal sheet.

Our rotation curve decomposition for this galaxy shows that it is definitely maximal. The baryons clearly dominate in the inner 2.2 scale lengths of the galaxy, with minimum contribution from the dark halo.

In the next and final chapter of this thesis, I present the key conclusions from this study of nearby disc galaxies and discuss the scope for future work.

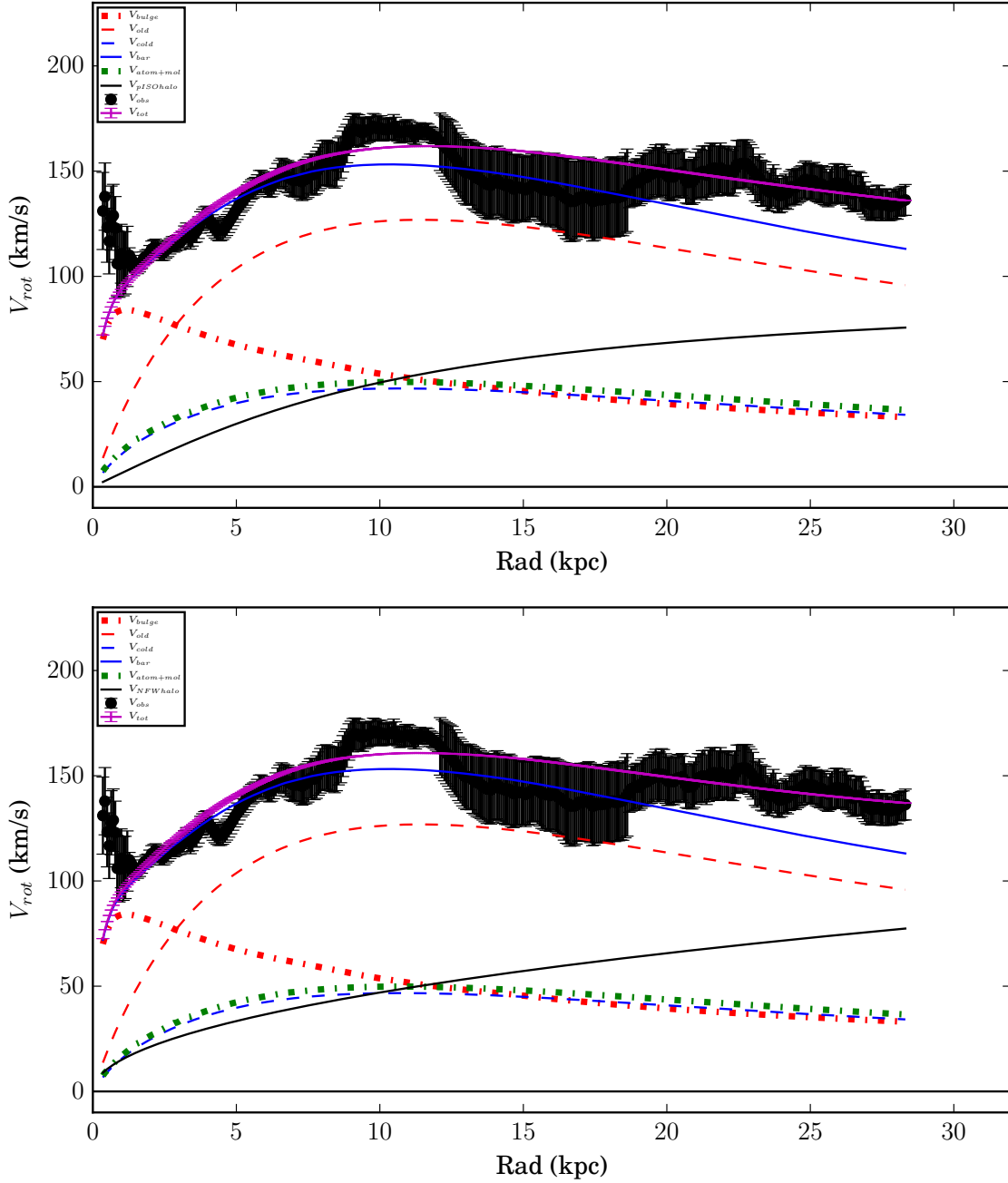


Figure 6.9: The rotation curve decomposition for NGC 5457 by fitting a pISO halo (top panel) and a NFW halo (bottom panel). Observed HI rotation curve is shown as black dots. The rotational velocity of the atomic + molecular gas is shown as the green dashed–dotted line. The rotation curve for the bulge is shown by the red dashed–dotted line. The hot and cold stellar disc rotational velocities are indicated using the dashed red and blue curves respectively. The solid red line represents the combined rotation velocity of the two stellar components (hot+cold). The fitted dark matter halo rotation curve is shown by the black solid line. The blue solid curve is the rotation curve from the total baryonic component: bulge+gas+disc. The magenta line represents the total rotational velocity: $V_{tot}^2 = V_{gas}^2 + V_{hot}^2 + V_{cold}^2 + V_{halo}^2$.

CONCLUSIONS

The main aim of this thesis was to resolve the disc-halo degeneracy. There is evidence from the age-velocity dispersion relation of thin disc stars from the solar neighbourhood that stars with ages < 3 Gyr show a rising velocity dispersion with typical dispersions of $10 - 12 \text{ km s}^{-1}$, and stars with ages $3 - 10$ Gyr have a constant dispersion of $\sim 20 \text{ km s}^{-1}$ (see Fig. 4.7 in Chapter 4). These two groups of stars represent two different thin disc populations with different kinematics: a kinematically cold component consisting of young, bright stars and a kinematically hot component of older stars. Previous studies that tried to break the disc-(dark halo) degeneracy considered the disc to be a kinematically homogeneous population of tracers. This led to a mismatch between the vertical velocity dispersion and the scale height, both of which need to refer to the same population of tracers. This mismatch led to an underestimation of the disc surface mass density.

For the first part of this project, we looked at a sample of K-giants in the solar neighbourhood. We wanted to ensure that there really do exist two thin disc components with different dispersions. Fitting two Gaussians to the W velocity histogram of the data revealed two components with W dispersions of $9.6 \pm 0.5 \text{ km s}^{-1}$ and $18.6 \pm 1.0 \text{ km s}^{-1}$. The two component fit was preferred over the one component fit which gave a dispersion of $13.0 \pm 0.1 \text{ km s}^{-1}$. Calculating the surface mass density using the dispersion of the single Gaussian fit rather than the dispersion of the hot component will underestimate the density by a factor of 2. This factor is high enough for truly maximal galaxies to be incorrectly classified as being submaximal.

We wanted to build on earlier works that used the surface mass density to break the disc-halo degeneracy, particularly the DiskMass survey (DMS, Bershadsky et al. 2010a) and work by Herrmann et al. (2008). These works were limited by the SNR of their data and would not be able to detect the two thin disc components with their data. We present the results of a survey of three nearby face-on disc galaxies – NGC 628, NGC 6946, and NGC 5457 using absorption line spectroscopy and planetary nebulae (PNe) to trace the kinematics of the thin disc. We obtained high SNR absorption line data with the VIRUS-W instrument on the 2.7m telescope at McDonald observatory (Fabricius et al. 2012). We had SNR of at least 70 per wavelength pixel in the radial bins that we analysed. The PNe allow us to trace the kinematics of the disc much further out than with IFU data, which are typically photon limited. We typically had 10 times more PNe per radial bin than Herrmann & Ciardullo (2009b). With such high quality data we were able to extract the

vertical velocity dispersions of the hot and cold thin disc components.

Our sample of galaxies were specifically chosen for being close to face-on. This helps us separate the vertical velocity dispersion σ_z from the in-plane components of the dispersion rather easily. These galaxies are all large systems, and we were able to obtain data in several radial bins, typically out ~ 4 radial scale lengths (3 scale lengths in the case NGC 5457). The results from the analysis of the absorption spectra were consistent with the results from the PNe. We find a kinematically hot disc component that radially declines as an exponential with twice the galaxy's scale length. This trend is consistent with the galaxy having a constant scale height and M/L .

Two of our galaxies (NGC 628 and NGC 5457) were analysed by Herrmann & Ciardullo (2009b). We were therefore able to directly compare our results with theirs. In the case of NGC 628, our central surface mass density was ~ 3 times larger than the value got by them. The effect was much larger in NGC 5457, where our central surface mass density was ~ 4 times higher than their value. The σ_z values for our single Gaussian fits in both galaxies agree quite well with the values got by Herrmann & Ciardullo (2009b).

For each galaxy, we calculate the M/L in several optical bands in each radial bin. We find the M/L to be constant (within errors) in each galaxy. We believe that this is the first dynamical study that gives the observed M/L as a function of radius in these nearby galaxies.

We decompose the rotation curve for these galaxies and find all of them to have a maximal disc. The inner 2.2 scale length of the galaxy are clearly dominated by baryons, with minimum contribution from the dark halo.

Fig. 7.1 compares the results from our three galaxies with the results from the DMS and an older work by Bottema (1993). This plot taken from Bershadsky et al. (2011) shows the central vertical velocity dispersion obtained from their sample of face-on galaxies as a function of the maximum rotational velocity of the galaxy. The solid black lines are the typical values of oblateness h_R/h_z observed in galaxies. The points in black are the DMS galaxies. The open red circles are galaxies from the Bottema (1993) sample. If the galaxies are maximal, they should lie in the shaded region in this plot. Since all the DMS galaxies typically lie below this shaded region, they conclude that their galaxy discs are submaximal. I overplotted my three galaxies on this plot in blue, using the central vertical velocity dispersion of the hot component. Our galaxies very comfortably lie in the shaded maximal disc region.

This has been a very challenging, observationally intense project. We have a few more northern hemisphere spirals with both IFU and PNe data, as well as three spiral galaxies in the southern hemisphere with IFU data from the WiFeS spectrograph. Analysing these galaxies is our immediate goal for the future. Increasing our sample size will definitely put our results on a firmer basis. Apart from applying our two component analysis to other nearby disc galaxies, there are two interesting projects that we are keen on expanding into. I discuss these projects briefly in the next section.

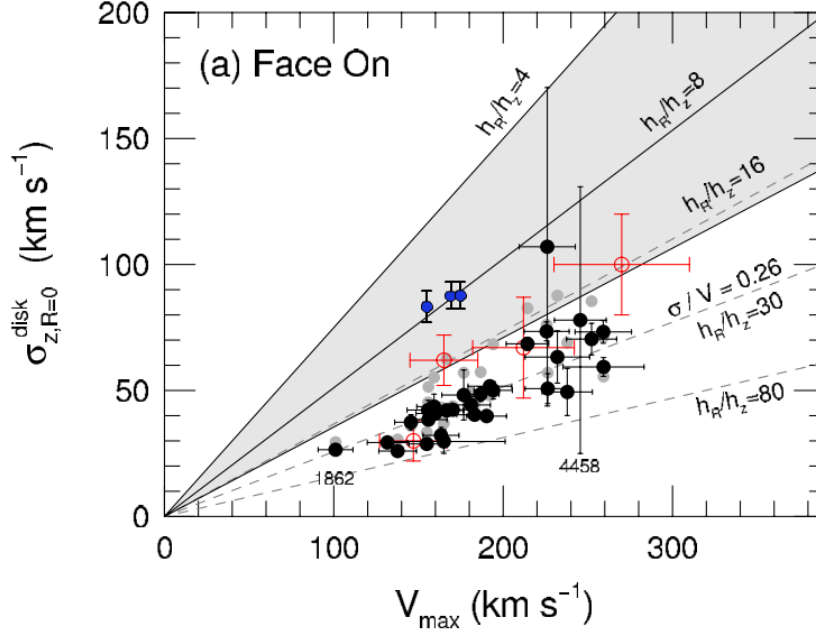


Figure 7.1: The plot of the central vertical velocity dispersion against maximum rotational velocity of the galaxy take from Bershady et al. (2011). The points in black are the $\sigma_z(0)$ values from galaxies in the DMS sample. The red open circles are the galaxies analysed by Bottema (1993). The grey circles are σ_{LOS} for the DMS galaxies, uncorrected to find σ_z . The shaded region is where maximal discs would lie. Our three galaxies are overplotted on this figure as blue data points using the $\sigma_z(0)$ of the hot component. These clearly lie in the expected 'maximal disc region'.

7.1 Future Work

7.1.1 Tracing the Onset of Thin Disc in Spiral Galaxies

The multiple component fitting routines used to discriminate between the cold and hot components can be applied to answer other science questions. Specifically, we can use this approach to trace the onset of the thin disc in higher redshift galaxies. We are interested in the assembly of the discs of large spirals like the Milky Way. We know that, in the Milky Way, the stars of the thick disc formed 10 to 12 Gyr ago, corresponding to redshifts $z = 2$ to 3. Thin disc formation did not begin until later, about 9 Gyr ago, corresponding to $z = 1.5$ (e.g. Bensby et al. 2014). There is some evidence for a pause in the star formation rate between the end of the thick disc formation and the onset of thin disc formation.

Figure 2 shows the recent results on the turbulence in star-forming high- z discs. The gas turbulence decays gradually, from about 70 km/s at $z = 2.5$ to about 30 km/s at $z = 1$ (Wisnioski et al. 2015). At the high redshift end of this interval, the high turbulence is consistent with the high stellar velocity dispersion observed in the Galactic thick disc. The low redshift end is already into the epoch of thin disc formation in the Milky Way, and the lower turbulent velocity dispersion is consistent

with the velocity dispersion of the old thin disc in the Galaxy.

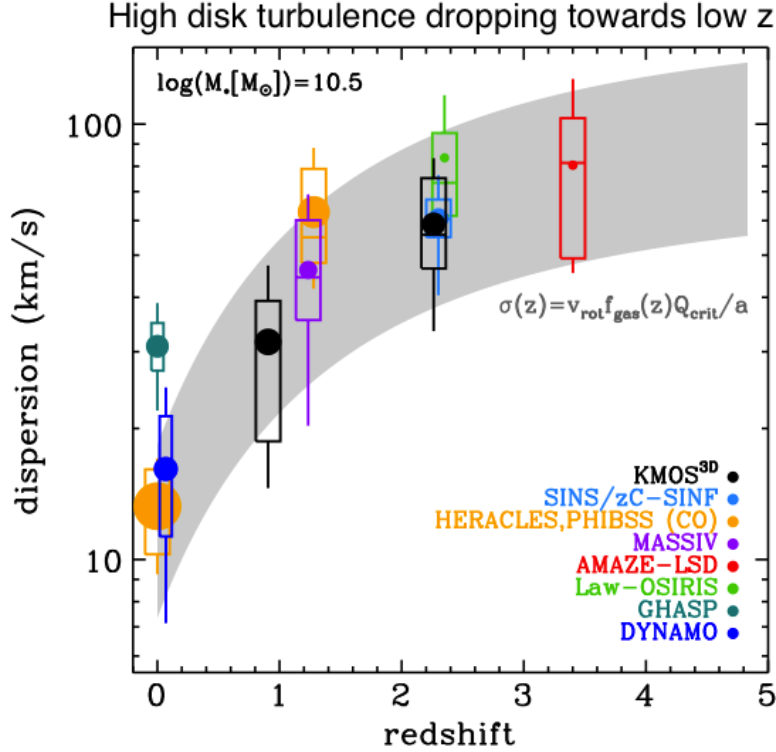


Figure 7.2: The 3D dispersion of gas as a function of redshift. This plot is taken from Wisnioski et al. (2015). From studies in the Milky Way it is known that the thick disc formed around $z = 2$ to 3 and the thin disc formation did not begin until $z = 1.5$.

The thin disc is the dominant stellar component in later-type spiral galaxies, and it would be very interesting to know when the thin disc begins to form in spirals other than the Milky Way. I believe that this can now be determined dynamically. I propose to undertake integrated light spectroscopy of near-face-on galaxies in the redshift range from about 0.8 to 1.3, at a rest wavelength of about $5200 \text{ \AA}$. The goal is to determine the redshift of onset of thin disc formation.

Before the thin disc starts to form, the integrated absorption-line spectra of the discs will be dominated by the thick disc, forming from the turbulent gas (Wisnioski et al. 2015). Shortly after the thin disc has begun to form, the integrated disc spectra will have two components: the thick disc (now a few Gyr old) and the young thin disc. The technique I developed during my PhD for measuring multiple velocity dispersion components from integrated light spectra will be ideal for detecting whether the thin disc is already present in these galaxies.

The Mgb region, which we have used for the analysis of nearby galaxies, lies in the J-band at $z \sim 1.3$. Using a sample of spiral galaxies in the redshift range 0.8 to 1.3 (from the COSMOS survey or the DEEP Groth strip survey), we propose to use high signal-to-noise ratio data from IFU spectroscopy to determine the redshifts

at which we start to see the thin disc kinematics appear. The challenge would be to detect the emerging kinematically colder thin disc against the hotter thick disc which formed somewhat earlier.

From previous experience of carrying out the double component fit in nearby galaxies, a resolution of $R \sim 4000$ would be sufficient to decompose NIR spectra of the discs into contributions from a newly formed thin disc with a velocity dispersion of about 30 km/s and the somewhat older thick disc with about double the velocity dispersion. There are a few different instruments that would be ideal for this work in terms of resolution and wavelength coverage, such as the NIFS spectrometer on Gemini-North and the FIRE spectrometer on Magellan 1. XSHOOTER on VLT, is another great instrument for this work. Australia has recently entered into a strategic partnership with ESO, which allows Australian scientists to apply for time on ESO telescopes. Therefore, we will be applying for time on XSHOOTER during the next proposal period to carry out a feasibility study for this project.

This project will considerably advance our understanding of galaxy assembly by observationally answering the question: at what redshift did the thin disc start to assemble?

7.1.2 Radial Change in Metallicity of the Hot Thin Disc

Another interesting project to pursue would be to study the radial trend in metallicity of the old thin disc. We have high quality integrated light data on three southern hemisphere spirals (NGC 300, NGC 6744, and M83) using the WiFeS instrument. The WiFeS is an IFU spectrometer on the 2.3m telescope at Siding Spring (Dopita et al. 2007). We observed these galaxies in the high resolution mode, which has a resolution of $R \sim 7000$. The data were obtained using the blue and red camera on the instruments. This gives us spectra around the Mgb absorption lines (~ 5170 Å), as well as the Ca-triplet lines (~ 8600 Å). In each galaxy we have good data in at least three radial bins. Similar to our VIRUS-W analysis, we can sum up all the spectra within a radial bin to produce a high SNR spectrum representative of that radial bin. We then use pPXF to fit a hot and cold thin disc component to the data. We can then use the hot and cold components returned by pPXF to measure the metallicities in these radial bins for each component. There are several works that study the trend in metallicity using HII regions in nearby galaxies (eg Searle 1971, Bresolin et al. 2009 etc.). However, these typically sample the young stellar population. There is currently little research that looks at the radial trend in metallicity of the older thin disc stars (ages $\gtrsim 3$ Gyr) in spiral galaxies. Pilkington et al. (2012) examine radial and vertical metallicity gradients using a suite of disc galaxy hydrodynamical simulations. They find that flatter gradients are observed at redshift zero when comparing older stars with the younger stars forming today, consistent with expectations of kinematically hot simulations, but different to the results observed in the Milky Way (Pilkington et al. 2012). Recent work by Anders et al. (2017) used asteroseismic and spectroscopic observations of red-giant stars in the Milky Way to measure the age dependence of the radial metallicity distribution. They find that stars with ages of 1–4 Gyr show a steeper gradient in metallicity

compared to stars with ages 6 – 10 Gyr. However, they note that their age measurements are more uncertain for the older stars. Hence, the results are still debatable and not conclusive. We can essentially fill that gap in literature by measuring the metallicity from our absorption line spectra for the hot component in each radial bin.

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Appendices

Contribution of different parts of the CMD to the integrated spectra of the disc

The Galactic disc near the sun is a composite population, with stars covering the whole range of age from very young to about 10 Gyr. The stellar population is similarly composite in other star-forming galaxies; the details depend on the local star formation history. As a guide to the relative contributions to the integrated light in external galaxies, from young and old giants, bright main sequence stars, and the main sequence below the old turnoff, we use the IAC-STAR synthetic CMD computation code to evaluate the contributions from the different parts of the CMD to the integrated light of the disc for a star formation history like that described in section 1 (see Fig. 2.1 and related text). The region of the spectrum that is mostly used for integrated light spectroscopy of the disc is around 5200Å near the Mg b band. We are therefore interested in the relative contributions to the integrated light at the V-band.

Fig. 2.1 illustrates the regions of the CMD that are populated by younger and older stars. We partition the CMD somewhat arbitrarily into 3 regions: the bright main sequence ($M_V \leq 4, B - V \leq 0.7$), the lower main sequence ($M_V > 4$) and the red giants ($M_V \leq 4, B - V > 0.7$). For each of these 3 regions of the CMD, we constructed the M_V luminosity function for the stars in the IAC simulated catalogue. For the adopted star formation history ($\propto \exp(-t/\beta)$ with $\beta = 20$ Gyr), the contributions from the three regions to the V-band light are: bright main sequence 37%, lower main sequence 10% and red giants 53%. The young giants (age ≤ 2 Gyr) contributed 16% of the total light, and the older giants contributed 37% of the total light. These relative contributions depend on the adopted star formation history. For a more nearly constant star formation history, with $\beta = 60$ Gyr, the younger and older giants contribute 16% and 32% respectively to the integrated light.

Although the spectra of stars around the main sequence turnoff do contribute to the equivalent widths of the absorption lines in the Mg b region, the red giants are the main contributors to the absorption lines in the integrated spectra from which the velocity dispersions are measured. This is why we chose to concentrate on the kinematics of the red giants in the solar neighbourhood in the present paper. Comparison of the integrated spectra of galactic discs with the spectra of individual giant

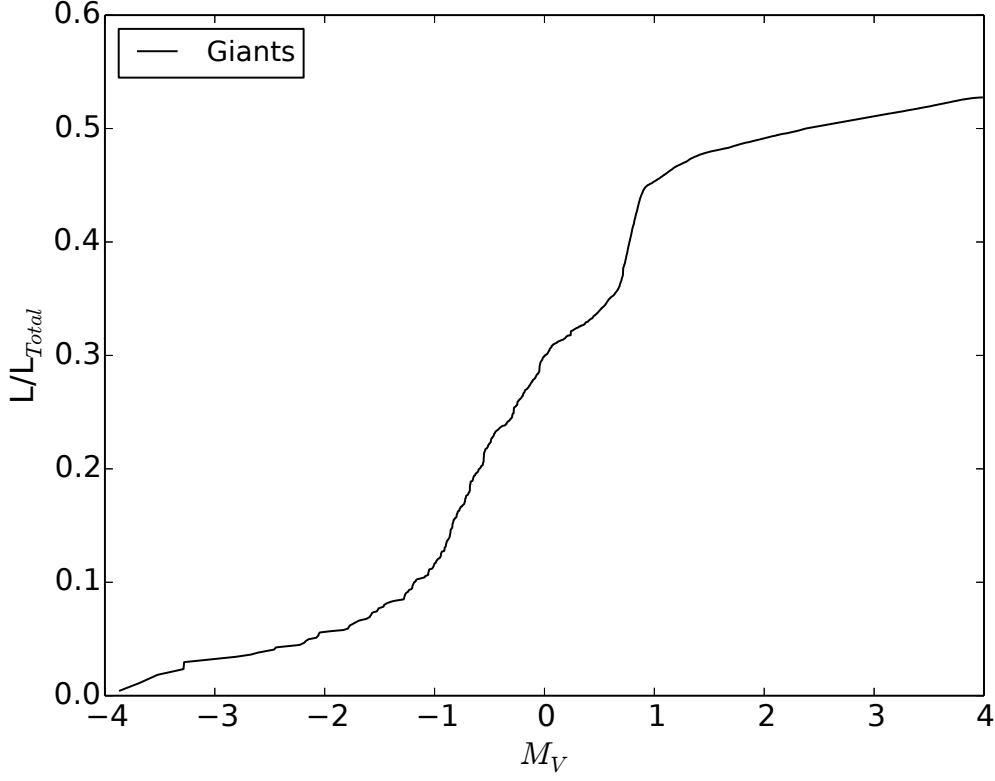


Figure A.1: Cumulative histogram of the integrated light of red giants derived from the IAC-STAR simulation. L_{total} is the total light from all stars. The giants provide about 53% of the total surface brightness of the disc, for the adopted star formation history $\beta = 20$ Gyr.

stars shows that the lines of the integrated spectra are diluted by the contribution of continuum light from the hotter main sequence stars.

The young giants contribute 30% to 35% of the total light from the giants. The point of this paper is that the contribution from these stars needs to be taken into account when measuring the velocity dispersion from the integrated light of external galaxies, to avoid underestimating the surface mass density of the galactic disc.

Effect of the cold layer on the equilibrium of the isothermal sheet

In Chapter 4 section 5, we derived the surface density of NGC 628 from the observed scale height and velocity dispersion, modelling the disc as a simple 1D isothermal sheet. For consistency with other authors, we ignored the gravitational field of the cold layer (gas and young stars). In this Appendix, we estimate the effect of the cold layer on the structure and surface density of the isothermal disc (see Binney & Tremaine II: problems 4.21 & 4.22).

B.1 The distribution function for the isothermal disc

The stellar energy is $E = v^2/2 + \Phi$, where v is the stellar velocity and Φ the potential. The distribution function has the form $f(E) \propto \exp(-E/\sigma^2)$ where σ is the stellar velocity dispersion. Write $\Phi = \sigma^2\phi$. The distribution function for the isothermal sheet is

$$f = \frac{\rho_o}{\sqrt{2\pi}\sigma^2} \exp(-v^2/2\sigma^2 - \phi).$$

The velocity distribution is isothermal and everywhere gaussian, and the density is

$$\rho(z) = \rho_o \exp(-\phi)$$

where we take $\phi(0) = 0$. Write $z/h_z = \zeta$. The 1D Poisson equation is

$$\frac{d^2\Phi}{dz^2} = 4\pi G\rho$$

or

$$2 \frac{d^2\phi}{d\zeta^2} = \frac{8\pi G\rho_o h_z^2}{\sigma^2} \exp(-\phi)$$

or

$$2 \frac{d^2\phi}{d\zeta^2} = \exp(-\phi) \tag{B.1}$$

for $h_z^2 = \sigma_z^2 / (8\pi G \rho_o)$. Equation B.1 has the solution $\phi = \ln \cosh^2(\zeta/2)$, $d\phi/d\zeta = \tanh(\zeta/2)$, and

$$\rho = \rho_o \exp(-\phi) = \rho_o \operatorname{sech}^2(\zeta/2) = \rho_o \operatorname{sech}^2(z/2h_z).$$

At large $|z|$, $\rho \rightarrow \exp(-|z|/h_z)$. The surface density is $\Sigma = 4\rho_o h_z$, and the vertical force is $K_z = -8\pi G \rho_o h_z \tanh(z/2h_z)$.

B.2 The isothermal sheet in the presence of the cold layer

We model the disc as an isothermal sheet of hot disc population, plus a thin layer of cold disc population (gas and young stars) with surface density Σ_C . The total density is then

$$\rho_D(z) + \Sigma_C \delta(z)$$

where $\rho_D(z)$ is the density distribution of the isothermal sheet in the presence of the extra component. The vertical force and potential for the cold layer are:

$$\begin{aligned} K_z &= -2\pi G \Sigma_C z/|z| \\ \Phi_C &= 2\pi G \Sigma_C |z| \end{aligned}$$

With the extra component, the energy is $E = v^2/2 + \Phi$, where $\Phi = \Phi_D + \Phi_C$ and Φ_D is the potential of the hot isothermal sheet. Write $\Phi = \sigma_z^2 \phi$. The distribution function for the isothermal sheet is

$$f_D = \frac{\rho_o}{\sqrt{2\pi\sigma^2}} \exp(-v^2/2\sigma_z^2 - \phi)$$

and

$$\rho_D = \rho_o \exp(-\phi). \quad (\text{B.2})$$

Write $z/h_z = \zeta$. The 1D Poisson equation for the isothermal sheet is

$$2 \frac{d^2 \phi_D}{d\zeta^2} = \frac{8\pi G \rho_o h_z^2}{\sigma_z^2} \exp(-\phi_D - \phi_C)$$

where $\phi_C = 2\pi G \Sigma_C h_z |\zeta|/\sigma_z^2$. With $\phi = \phi_D + \phi_C$, equation B.2 becomes

$$2 \frac{d^2 \phi}{d\zeta^2} = \frac{8\pi G \rho_o h_z^2}{\sigma_z^2} \exp(-\phi) \quad (\text{B.3})$$

for $|\zeta| > 0$. The solution to equation B.3 gives the potential ϕ and the density distribution ρ_D for the isothermal sheet in the presence of the cold layer. We look for a solution of the form

$$\phi = \ln \frac{\cosh^2(|\zeta|/2 + b)}{\cosh^2 b} \quad (\text{B.4})$$

such that $\phi(0) = 0$ and $\phi' = \tanh(|\zeta|/2 + b) \rightarrow 2\pi G h_z \Sigma_C / \sigma_z^2$ as $\zeta \rightarrow 0$. Equation

B.4 is a solution if

$$\tanh(b) = 2\pi G h_z \Sigma_C / \sigma^2 \quad (\text{B.5})$$

and

$$8\pi G \rho_o \cosh^2(b) h_z^2 / \sigma_z^2 = 1. \quad (\text{B.6})$$

The density of the isothermal sheet is then

$$\rho_D(\zeta) = \rho_o \cosh^2(b) \operatorname{sech}^2(|\zeta|/2 + b). \quad (\text{B.7})$$

and its surface density is

$$\Sigma_D = \frac{4\rho_o h_z}{1 + \tanh(b)}. \quad (\text{B.8})$$

B.2.1 The surface density of the isothermal disc

At large $|z|$, equation B.7 becomes

$$\rho_D \propto \exp(-|z|/h_z)$$

and the photometric scale height is approximately equal to the natural scale parameter h_z defined in equation B.6. From equations B.6 – B.8, we eliminate the parameter ρ_o . In terms of its surface density Σ_D and the observables Σ_C , h_z and σ_z , the density distribution of the isothermal sheet is

$$\rho(z) = \frac{\sigma_z^2}{8\pi G h_z^2} \operatorname{sech}^2(|z|/2 + b), \quad (\text{B.9})$$

the scaling equation B.6 becomes

$$\Sigma_T = \Sigma_C + \Sigma_D = \frac{\sigma_z^2}{2\pi G h_z}, \quad (\text{B.10})$$

and equation B.5 defines the offset parameter b . From equations B.5 and B.10, b is approximately the surface density fraction $\Sigma_C/(\Sigma_C + \Sigma_D)$ in the cold layer.

B.3 Summary

- In the presence of the cold gas layer Σ_C , the isothermal sheet has the form

$$\rho(z) = \frac{\sigma_z^2}{8\pi G h_z^2} \operatorname{sech}^2(|z|/2h_z + b)$$

where $\tanh(b) = 2\pi G h_z \Sigma_C / \sigma_z^2$.

- The total surface density $\Sigma_T = \Sigma_C + \Sigma_D = \sigma_z^2/(2\pi G h_z)$.

- The scale parameter h_z for the isothermal sheet $\approx$ the exponential scale height for the hot disc.
- The radial dependence of $\sigma_z^2(R) \propto \Sigma_T(R)$, if h_z is constant.

Effect of the cold layer on the surface mass density of the Milky Way Disc

In Chapter 2, while calculating the surface mass density of the disc of the Milky Way, we did not take into account the influence of the cold sheet, since we were merely comparing our surface densities with previous studies that estimated the density. Our goal was to check our hypothesis that there really did exist two stellar thin disc components with very different vertical velocity dispersions.

Later, in Chapter 4, we reason that the discs of galaxies are made up of isothermal layers of gas, cold stellar disc and the hot stellar disc. Appendix B shows our detailed calculation on the influence of the cold layers on the calculated surface mass density of the thin disc. If we were to apply a similar analysis to our solar neighbourhood data using:

$$\Sigma_T = f\sigma_z^2/Gh_z$$

where, Σ_T is the total surface mass density of the disc (hot + cold components). Using $f = 1/2\pi$ for the isothermal case, we get $\Sigma_T = 42.7 \pm 8.5 \text{ M}_\odot \text{ pc}^{-2}$. However, from Appendix B we know that

$$\Sigma_T = \Sigma_{C,\text{gas}} + \Sigma_{C,*} + \Sigma_D$$

where, $\Sigma_{C,\text{gas}}$ is the surface mass density of the total gas, $\Sigma_{C,*}$ is the surface mass density of the cold stellar isothermal disc and Σ_D is the surface mass density of the hot stellar isothermal disc.

Using $\Sigma_{C,\text{gas}} = 12.6 \pm 1.6 \text{ M}_\odot \text{ pc}^{-2}$ (from McKee et al. 2015) and $\Sigma_{C,*}/\Sigma_D = 0.12$, assuming the star formation histories of NGC 628 and the solar neighborhood were similar, we get $\Sigma_{C,*} = 3.2 \pm 0.9 \text{ M}_\odot \text{ pc}^{-2}$ and $\Sigma_D = 26.9 \pm 7.7 \text{ M}_\odot \text{ pc}^{-2}$ for the Milky Way disc near the solar neighbourhood. Our value of $\Sigma_T = 42.7 \pm 8.5 \text{ M}_\odot \text{ pc}^{-2}$, using the isothermal model of the disc is somewhat closer to the Bovy & Rix (2013) estimate of the surface density than to earlier higher estimates of the surface density of the galactic thin disc (Flynn & Fuchs 1994, Holmberg & Flynn 2004).