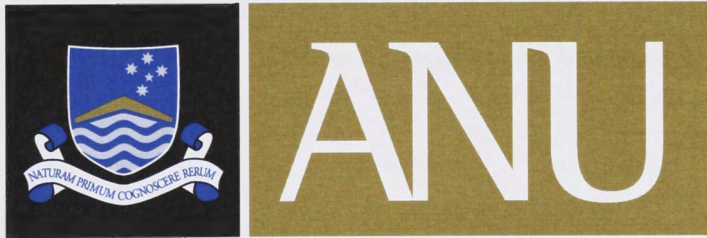


Dynamics of elliptical and bulge galaxies using planetary nebulae

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THE AUSTRALIAN NATIONAL UNIVERSITY

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

Declaration

This thesis is an account of research undertaken between July 2007 and March 2011. The work on the PN kinematics of NGC 1399 in Chapter 5 has already been published (McNeil et al. 2010).

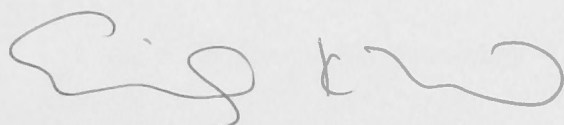
The measurement of the rotation of NGC 1399 in §5.2.7.1, including Fig.5.16 was done by L. Coccato.

The work in §5.3.2 is reproduced from a draft of Das, Gerhard, McNeil-Moylan et al. (2011, in prep) and also appears in the PhD thesis of P. Das (Das 2011).

Chapter 6, Chapter 7 and Chapter 8 contain text and figures that will be included in a series of publications still in preparation.

Where appropriate, I have cited and acknowledged contributions made by collaborators and colleagues. The remaining parts are my own work.

Except where acknowledged, the material presented is, to the best of my knowledge, original, and has not been submitted for a degree at any university.

A handwritten signature in dark ink, appearing to read 'Emily Moylan', with a stylized flourish at the end.

Emily Moylan
August 8, 2011

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Abstract

We explore the dynamics of four elliptical and bulge galaxies. We focus on the outer parts where the mass is dark-matter dominated and the orbital structures describe the formation histories. We combined the measured kinematics of planetary nebulae (PN) with integrated light kinematics and photometry to provide a radially complete set of compatible observational constraints.

The sample is comprised of NGC 1399, NGC 3923, NGC 1316 and NGC 4594. NGC 1399 is one of the nearest cD galaxies and is an archetypal, slow-rotating, giant elliptical. NGC 3923 has a spectacular system of 22 shells left over from a merger. NGC 1316 is the brightest cluster galaxy in Fornax and is a recent merger remnant. NGC 4594 (M104, Sombrero) has a large bulge and a nearly edge-on dusty disk. In each case, we study the rotation and dispersion profile of the kinematic tracers. For the first three galaxies, we explore the dark matter content and the orbital structure using dynamical models.

We generated four PN velocity catalogs plus a catalog of PNe in NGC 1317. The kinematics of the four galaxies describe the varied formation histories of the sample. The marginal rotation in NGC 1399 contrasts with the clear rotation signal in NGC 1316. The PN in NGC 4594 confirm observations of non-cylindrical rotation. Rotation in the outer parts of NGC 3923 is surprising given the alignment and regularity of the shell system. The halo dispersion profiles range from gently rising in NGC 3923 to steeply falling in NGC 1316.

We performed Jeans modeling of NGC 3923 and NGC 1316 and applied the made-to-measure N-body code, NMAGIC, to NGC 1399. All of our models require dark matter in the outer parts in order to fit the observed PN kinematics. Comparing the models and observations, we use the four galaxies in this sample to learn about the formation and evolution of elliptical and bulge galaxies. Based on this sample, we find that very evolved systems like cD galaxies have triaxial distributions and marginal rotation. In contrast, NGC 1316, the dominant galaxy in its subcluster, shows very dif-

ferent dynamics: strong rotation and an axisymmetric distribution. Clearly the later stages of hierarchical assembly have a big impact on the dynamics of early-type galaxies. Our observations of NGC 3923 indicate that shells around galaxies can be formed in less restricted circumstances than previously thought (Hernquist & Quinn 1989) and they are robust. Bulge galaxies have characteristics in common with both elliptical and disk galaxies. The rotation of the PN sample in NGC 4594 underscores the impact of scale on the classification of these objects— near the disk the bulge rotates strongly, but in the outer parts it has more in common with an elliptical. Dark matter composes between 5% and 31% of the total mass within $1 R_e$. The transition to dark matter dominance occurs in the range of 2-4 R_e in agreement with the result from Gerhard et al. (2001).

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Chapter 1

Introduction

This thesis is written in two parts corresponding to the methods developed to measure galaxy halo dynamics and to their application to a sample of elliptical and bugle galaxies. In Part I we cover the various observational methods and modeling techniques that have been developed to learn about the outer parts of early-type galaxies, focusing on methods used to acquire planetary nebula velocities at large radii. In Part II, we apply the methods of Part I to four galaxies and present the planetary nebula velocity catalogs for the sample. We compare our observations to a range of models in three cases and address the formation histories of the galaxies.

1.1 Knowns and unknowns with early-type galaxies

At first glance, early-type galaxies (ETGs) appear as smooth, nearly-structureless, ellipsoidal stellar systems. Their projection onto the celestial plane masks their varied nature as triaxial bodies in triaxial dark matter halos. The early-type classification includes elliptical and S0 (lenticular) galaxies. When examined closely, ellipticals display important structural distinctions including the shape of their isophotes (boxy or disky, see Table 1.1 and discussion later in the text) and the index of their radial light profile, which depends on absolute magnitude (Kormendy et al. 2009). S0 galaxies can be nearly indistinguishable from ellipticals when viewed face-on, but show a distinctive bulge-disk substructure when seen edge-on.

The Sombrero galaxy (NGC 4594, M104) is a spiral galaxy (SAa, de Vaucouleurs et al. (1991)) with a massive bulge. The bulge resembles an elliptical galaxy, and the stellar populations of bulges and ellipticals are similar. However, important differences are apparent when the two types are seen in the V/σ - ϵ

plane. Fig. 1.1 (Kormendy & Kennicutt 2004) illustrates the relative importance of rotation and random motion as a function of ellipticity. SA bulges occupy a higher part of the plot than ellipticals indicating the increased importance of rotation. This is consistent with our perception of the formation mechanisms of these objects— ellipticals form in mergers leading to higher dispersion values while disk galaxies, regardless of the size of the bulge, are dominated by their rotation. The formation mechanism of S0 galaxies is not well understood— some evidence supports mergers and some gas draining of disk galaxies. In either case, they represent a missing link between spirals and ellipticals.

ETGs are observed to be concentrated in dense environments like the center of clusters (Oemler 1974). This result supports the concept of elliptical galaxies forming as the result of mergers (Toomre 1977; White & Rees 1978; Barnes 1989) because galaxies in dense environments (like groups and clusters) have more opportunities to interact and form ellipsoids.

The light from ETGs is usually dominated by red, older stellar populations compared to the light from disk galaxies. The center is often redder than the edges, which indicates a gradient in metallicity. These objects have a low gas content compared to disk galaxies because the merger event initiated a burst of star formation that drained the gas from the system. Studies of ETGs are facilitated by the relatively simple morphology and low dust extinction, but the paucity of cool gas challenges kinematic measurements at large radii.

Rather than being prolate and oblate variations on a theme, ETGs show a variety of unique characteristics. We observe that 10-20% of ETGs display over-densities of light in their halos which represent systems of shells or ripples caused by merger events (Priour 1990). At the center of clusters, a class of galaxies called cD displays a light excess in the outer parts compared to the common $R^{1/4}$ profile. Many late-type systems display a bulge at the center that shares some traits with early-type galaxies. In the case of S0 galaxies, these bulges dominate the light while the dynamics of the system are still strongly influenced by the disk of the galaxy.

Even the general population of ETGs divides itself into two classes: slow and fast rotators. Fast rotators represent $\sim 86\%$ of early-type galaxies according to Emsellem et al. (2011). The dichotomy is a syndrome characterized by a list of symptoms summarized in Table 1.1, but the underlying cause is not well understood. The reason for the divide is one of many areas to be explored in the formation and evolution of ETGs. There is growing evidence that isophotal shape classification is not well correlated with kinematic behavior, which supports the adoption of an updated galaxy classification system that emphasizes rotation instead of morphology (Emsellem et al. 2011).

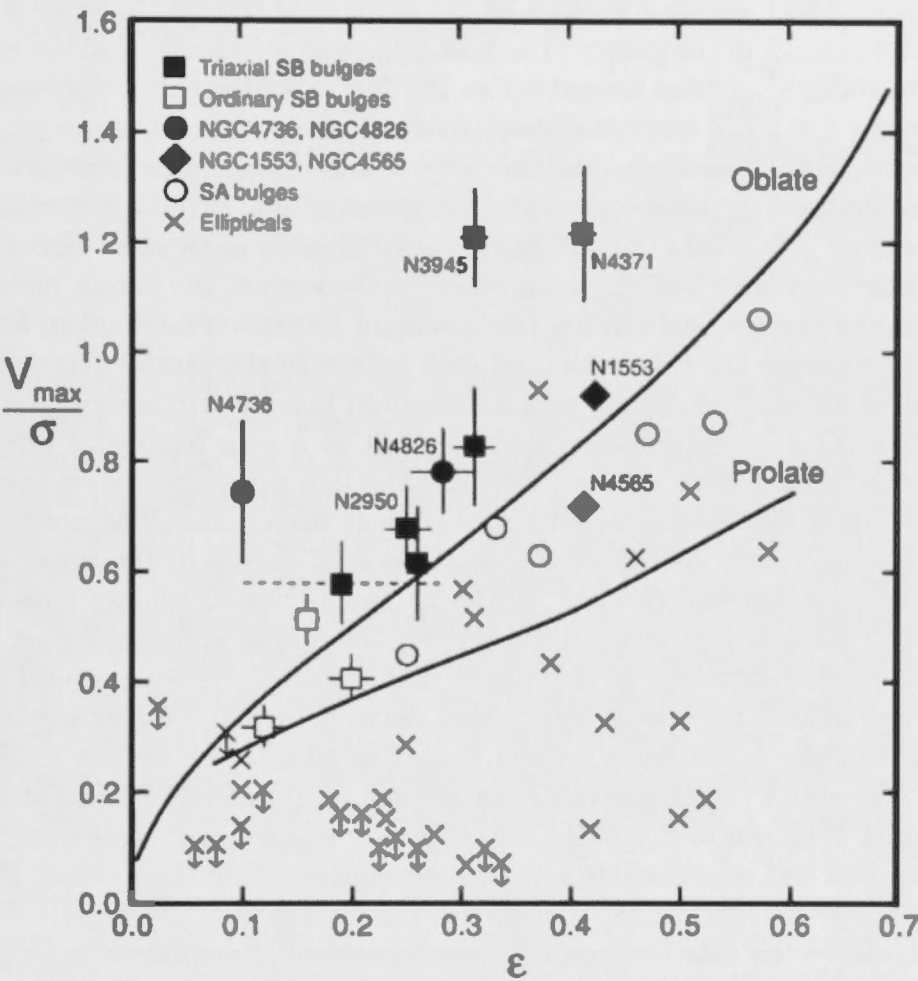


Figure 1.1 Comparison of V/σ ratio to ellipticity for a range of ellipsoidal stellar systems. V/σ indicates the relative importance of rotation and random motion in the dynamics of the galaxy. ϵ is defined as $1 - \text{apparent axial ratio}$. The hollow circles represent the bulges of galaxies like NGC 4594 and the crosses (generally lower on the plot for a given ellipticity) show elliptical galaxies. This plot is taken from Kormendy & Kennicutt (2004).

This issue is being addressed by the ATLAS^{3D} team (Cappellari et al. 2010) among others, and their findings will be important to our understanding of elliptical galaxies.

We are still learning about when elliptical galaxies form and on what timescale. The formation redshift of the stars need not be the same as the assembly redshift of the galaxy. The best estimates are that 50% of the stellar mass in today's galaxies assembled in the $0 < z < 1$ interval and another 40% in the $1 < z < 4$ interval (Pérez-González et al. 2008). There is ongoing research into the relative importance of wet and dry mergers (mergers with and without gas respectively) in the formation of ETGs (Ciotti et al. 2007; Forbes et al. 2007; Tal et al. 2009). We would like to know more about how the stellar populations of ellipsoids relate to elements of the parent material.

Merging and interactions are the dominant formation mechanism for the galaxies addressed in this work, and each galaxy in the sample represents a class of ellipticals associated with a formation history. Highly evolved systems like cD galaxies demonstrate the result of a long history of mergers. Oser et al. (2010) show galaxies assemble through a few dissipative mergers early in their history followed by many minor accretions. The position of cDs near the center of the cluster and the light excess in the outer parts both indicate that galaxies like NGC 1399 in the Fornax cluster have been merging with many galaxies and represent something approaching an end-state for stellar systems. It is thought that the shell systems around ellipticals are created by a weak interaction between an elliptical galaxy and a smaller object— in unusually regular cases like NGC 3923, we can make assumptions about the geometry of the interaction (Quinn & Hernquist 1987; Hernquist & Quinn 1988). NGC 1316 shows signs of being a recent merger including dust and intermediate age globular clusters (Goudfrooij et al. 2001). Remarkably for a giant merger remnant, this galaxy is in the outer suburbs of its cluster— we may be seeing an evolved central group galaxy falling into the Fornax cluster with the rest of its group (Drinkwater et al. 2001). As the brightest galaxy in the cluster, we expect NGC 1316 to represent a kind of juvenile cD galaxy, although in this case it could only become the dominant galaxy in its cluster by merging with NGC 1399. The bulge of NGC 4594 might have formed in a major merger followed by the disk settling from the leftover dust. How do the bulge's dynamics differ from the other systems in our sample without disk components?

Until recently, the listed unknowns have hinged upon understanding the somewhat complicated physics of baryonic mass assembly. However, the slightly-simpler, dissipationless, hierarchical assembly of dark-matter halos still masks some of the basic parameters of these galaxies. We do not yet understand the structure and composition of the dark matter around ETGs.

Table 1.1 Observed dichotomy in early-type galaxies.

	LUMINOUS ELLIPTICALS	FAINT ELLIPTICALS
Isophotes	Boxy	Disky
Velocity Distribution	Anisotropic, little rotation	Rotation about an axis
Luminosity Profile	Shallow central cusp	Steep central cusp
Color	Redder	Bluer
Metallicity	Higher	Lower
Intrinsic Shape	Triaxial	Oblate, flattened by rotation

* Summary of the dichotomy observed in early-type galaxies. This table is recreated from Table 1.1 in Das (2007).

The distribution could be smooth or clumpy or cuspy. In the inner parts, studies using strong and weak lensing indicate that $\sim 30\%$ of the mass is dark within $1R_e$ (Gavazzi et al. 2007; Barnabè et al. 2009). Dynamical models indicate fractions of 10-50% dark matter within $1R_e$ (Gerhard et al. 2001; Thomas et al. 2007). Comparisons to stellar population mass-to-light estimates imply dark matter content of 30% within an effective radius (Cappellari et al. 2006). We struggle against observational limits to measure the transition to dark-matter dominance as we move outwards in the mass profile. We expect 80-90% of the matter to be dark at the edges of the galaxy using total mass estimates from hot X-ray gas (Das et al. 2010). It is unknown if the point of transition from baryonic to dark matter occurs at a predictable scale radius, though Gerhard et al. (2001) estimated that the crossover occurs between 2-4 R_e .

Despite research into DM distributions, the evidence is occasionally controversial. Remarkably, Romanowsky et al. (2003) noted the possibility of NGC 3379 being an early-type galaxy without dark matter. Models constrained by newer observations from the planetary nebula spectrograph (PN.S), an instrument on the WHT dedicated to measuring PN velocities in nearby galaxies, show that the data are consistent with 30-50% dark matter within $4R_e$ and the importance of considering strongly anisotropic systems (Weijmans et al. 2009; de Lorenzi et al. 2009). NGC 3379 has proved a notable example on the frontier of what is known and unknown about dark matter and evidence that kinematic data from the outer parts of early-type galaxies are essential if we are to understand how much of the mass is dark and how it is distributed. This is exactly the area that we will explore in this work.

Our growing appreciation of the role of dark matter in ETGs is countered by the difficulty of measuring the mass profile at large radii. At the radii

where dark matter seems to dominate the mass and the long-dynamical-timescale orbits promise a window into the formation history of the galaxy, we are unable to measure the kinematics from integrated stellar light. As the community learns more about the complexities of these systems, the limiting factors become more apparent. In order to study ETGs, we require innovation in observational and modeling techniques.

1.2 Dynamical Models

The dynamics of a galaxy are completely described by its distribution function, $f(\mathbf{x}, \mathbf{v}, t)$ (Binney & Tremaine 1987), which specifies the position and velocity of every star. Broadly speaking, we model a galaxy by beginning with an initial guess about its distribution function and adjusting it until the model matches observations of the galaxy.

In general, there is more than one successful model for the observations because mass, orbital structure and shape are inherently degenerate. By adding in independent information about the mass profile and then making assumptions about the anisotropy or the intrinsic shape, we can break the degeneracy to find a unique fit to our observations. It is helpful to have extra information about the orientation of the galaxy (using a disk or the shell system) because projection effects contribute to the degeneracy, but the mass-anisotropy degeneracy is intrinsic.

Dynamical models range from very simple to very sophisticated. In this work, we will be using Jeans models and NMAGIC, a made-to-measure code with χ^2 -treatment of observational errors. The Jeans equations are analogous to Euler's equations of fluid dynamics, but they are used to model the dynamics of the stars in a galaxy (Binney & Tremaine 1987). Without addressing the distribution function directly, these types of models require us to make strong assumptions about the symmetry of the galaxy in velocity and configuration space. It's possible to find a Jeans model that matches our observations of the density and the kinematics but doesn't correspond to a physically possible distribution function (i.e. one that is positive everywhere).

Another one of the difficulties of Jeans modeling is finding consistent tracers for the density and the kinematics that span the relevant range of radii. Consider the example of the spherical, non-rotating, constant-anisotropy Jeans equation,

$$\frac{1}{\rho} \frac{d(\rho \sigma_r^2(r))}{dr} + 2 \frac{\beta \sigma_r^2(r)}{r} = - \frac{d\Phi}{dr}, \quad (1.1)$$

where ρ is the spatial density, σ_r is the velocity dispersion, and Φ is the total

potential. β is the anisotropy of the velocity distribution, $\beta \equiv 1 - \sigma_\theta^2/\sigma_r^2$, where σ_θ is the azimuthal velocity dispersion and σ_r is the radial velocity dispersion. The left-hand-side is deals with whatever observable we have selected as the tracer. On the right-hand-side, the potential will address our questions about the total mass content of the system, and it is the same regardless of what tracers are used. For the terms on the left-hand-side, we must select a tracer that allows us to measure density and kinematics from the center of the galaxy to the halo. Obvious candidates like stars do not extend to the outer halo with sufficient signal-to-noise. We can only mix-and-match observables if we believe that they follow the same underlying distribution. This issue is addressed in §1.3.

Jeans models are applied to NGC 3923 and NGC 1316 in §6.3 and §7.3 respectively. We constrain these models with observations of the projected light distribution and velocity dispersion measurements of integrated light and spatially binned planetary nebulae.

Made-to-measure (M2M) techniques (Syer & Tremaine 1996; de Lorenzi et al. 2007) are evolutionary N-body methods that step through time adjusting the weights of the particles in the model until it walks towards the observational constraints. In principle, M2M approaches do not require *a priori* assumptions about the shape or orbital structure of the galaxy. In §5.3.2, we apply NMAGIC, a type of M2M model, to NGC 1399. The observational constraints used in these models include the projected light distribution, the first four moments of the velocity distribution (v , σ , h_3 and h_4) from integrated light, and dispersion measurements of spatially binned planetary nebulae and globular clusters.

In addition to the modeling methods that will be used in this work, there are several other popular techniques. Orbit-library based techniques like Schwarzschild (1979, 1993) models work by adjusting the weight on each of the possible stellar orbits in the galaxy until the model mimics the observations. Similarly, Saglia et al. (2000) and Kronawitter et al. (2000) used a library of distribution functions covering a range of anisotropies in a range of DM halos. By varying the two components and minimizing χ^2 , it's possible to identify a unique solution within their framework of assumptions. These models, along with the M2M techniques, differ from the Jeans modeling because they do not suppress the higher order information about the distribution function coming from the observations.

These techniques vary in complexity allowing us to select an approach that is appropriate for the observed situation of a galaxy. The disadvantages of each technique are due to the simplifying assumptions necessary to make the method practical and the ambiguity stemming from the flexibility of the method. In all cases, the modeling philosophy is to explicitly or implicitly

recreate the underlying distribution distribution function of a galaxy.

1.3 Observations of the phase-space distribution function

Our ideas about the formation histories of early-type galaxies meet reality when we constrain our models with observations. In order to correctly interpret dynamical models, we need observations of how much matter is in the galaxy and how that matter is moving. The phase-space distribution function is a complete dynamical description of a galaxy, and it can be measured in many ways. If we compare the collisionless Boltzmann equation (Binney & Tremaine 1987),

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0, \quad (1.2)$$

where f is the distribution function introduced in 1.2 and Φ is the total potential, and Poisson's Equation (Binney & Tremaine 1987),

$$\nabla^2 \Phi = 4\pi G \rho, \quad (1.3)$$

where G is the gravitational constant and ρ is the density, we see that these equations are interrelated. The potential, Φ , is found in both equations. The density in Boltzmann's Equation is found by integrating the distribution function over velocity space, and this can be compared to the ρ on the right-hand-side of Poisson's equation. From this comparison, we see that only part of the potential comes from the observed density of our tracer— we also need the kinematics to understand the mass distribution. The work in this project is motivated by this important point— we will be measuring kinematics for the outer parts of galaxies so that we are able to measure the total potential.

Since we are especially interested in the outer parts where the dark matter dominates, the observational constraints must extend from the core to the outer halo. The kinematics are measured with tracers— we must be confident that our tracers follow the same spatial distribution as the observable used for the mass distribution. This stipulation is more constraining than one might assume, and the following sections present various solutions.

1.3.1 Integrated Light

The most basic measurement of the mass distribution is from photometry of the stellar light. Different bands will bias our measurements towards a certain

1.3. OBSERVATIONS OF THE PHASE-SPACE DISTRIBUTION FUNCTION 9

space on the color-magnitude diagram. Depending on the star-formation history and metallicity profile, the mass-to-light ratio may vary with radius yielding an inaccurate estimate of the mass. Moreover, this measurement will only address the stellar component of the mass, and kinematics are required to learn about the total mass. The obvious solution is to measure the kinematics of the same stars used in the photometry through integrated light spectroscopy. Historically, these kinds of observations were done using long slits, and the line-of-sight velocity distribution was quantified by measuring line profiles of absorption lines, usually in the regions around Mgb or CaT. The light is dominated by K giants and so the spatial distribution of our kinematic tracer must shadow that of the K giants. By binning along the spatial dimension of the slit, the signal-to-noise ratio of the observations can be increased until we are able to measure higher-order moments of the distribution (see Chapter 3).

Unfortunately, as we move out into the outer halo, the signal-to-noise ratio drops and binning in radius effectively masks the quantities we are trying to measure. We can slightly extend the radial limit of integrated-light observations by using the increased signal-to-noise from Integral Field Units like SAURON and VIRUS-P. In general, long-slit spectra provide measurements for the first 2-3 R_e (Kronawitter et al. 2000), multi-slit spectroscopy provides line-of-sight velocity distributions out to 3 R_e (Proctor et al. 2009) and IFUs can take measurements at 4 R_e (Murphy & Gebhardt 2007; Weijmans et al. 2009).

The outer parts of early-type galaxies are dominated by dark matter; the halo is an environment where we can learn about the shape and composition of dark matter in ellipticals. The orbital structure in these parts is more indicative of the formation history of the system than that of the core. Since the halo is an area of particular interest, it is necessary to pursue alternative tracers that will extend our observations even further in radius.

1.3.2 Discrete tracers

One option for radially extending the kinematic measurements is to measure velocities of many individual objects and build up a discrete distribution. In general, the kinematic distribution and number-density distribution of discrete tracers would be combined with integrated light kinematics and stellar photometry from the central regions; in that case, the spatial distributions and kinematic behaviors must be consistent. Additionally, the line-of-sight velocity distribution will be quantified from this discrete distribution, so this approach is only valid when the sample size is large. We use objects like planetary nebulae and globular clusters because they are bright enough that

individual objects can be detected in nearby galaxies.

Planetary nebulae are a very useful discrete tracer. In the last 20 years, observational advancements have allowed large samples of PN velocities to be measured in the local volume. Up to 15% of their light is emitted at the $\lambda 5007$ [OIII] emission line (Dopita et al. 1992; Schönberner et al. 2010) making them exceptionally bright for an individual stellar object. They can be detected as far away as 100Mpc (Gerhard et al. 2005) and their number density and kinematics follow those of the stars (Coccato et al. 2009). Since they are directly tracing the stars, PNe can also be used to constrain the orbital structure of a dynamical model. More information is available in Chapter 2.

Globular clusters follow a different spatial distribution so their kinematics do not trace the same population as the stars (Harris 1991; Ashman & Zepf 1998; Brodie & Strader 2006). The globular cluster system is dominated by the blue component of a bimodal color distribution in most galaxies. The radial distribution of this component is flatter than the integrated light from the stars. However, in some galaxies the red globular cluster sample does follow the integrated light (Brodie & Strader 2006; Schubert et al. 2010), and we expect the kinematics of this subset to be comparable to those of the integrated light and the PNe. Any component in equilibrium can be used to constrain the potential, but only consistent tracers can be combined to make a more radially complete sample. In galaxies where the red GCs are in equilibrium (Schubert et al. 2010) and they follow the distribution and kinematics of the stars, they are an excellent tracer since ETGs can have populations of hundreds or thousands of globular clusters.

A typical long-slit spectroscopy bin may contain light from over 50,000 K-giants. The intrinsic statistics of these observations are strong. We expect this kind of measurement to accurately reflect the underlying velocity distribution of the stars, although the data may be less valuable depending on the photon signal-to-noise. This underscores an important distinction between integrated-light and discrete-tracer kinematics— even when our photon signal-to-noise is good, the tens or hundreds of objects in our globular cluster and planetary nebula samples may not be enough to give a good statistical representation of the population they are tracing.

1.3.3 X-ray gas

Early-type galaxies are usually gas-poor systems and their HI maps are not useful ¹. However, some ETGs have detectable amounts of hot X-ray gas. Although the hot gas is in the same potential as the stars, it does not follow the same spatial distribution. Therefore X-ray gas does not complement kinematic tracers like PNe and GCs in early-type galaxies, but, in some cases, it might fill an important role to help us understand the total mass of the system and that can help us constrain the distribution function. Using measured temperature and pressure and assuming hydrostatic equilibrium, we can infer the potential and, from that, the total mass of the galaxy.

Recently, some notable discrepancies between mass estimates from X-rays and dynamical models in the outer parts of ETGs have called into question the accuracy of X-ray mass estimates (Das et al. 2011, submitted to MNRAS). In NGC 4649 the circular velocity curve from X-rays is considerably higher than that fitted in the modeling. This difference may be due to the incorrect application of hydrostatic equilibrium, uncertainties introduced in the deprojection, a metallicity gradient in the X-ray gas, or outflows of gas. Payel Das, with whom I am collaborating, has investigated the use of X-ray gas to determine the potential of similar galaxies as part of her thesis work. While this subject is being explored, it is important to make independent estimates of the total potential.

1.4 Project Summary

The goal of this research is to address some of the questions presented in §1.1. In order to better understand the formation and evolution of early-type stellar systems, we want to understand the distribution of dark matter and its relation to the mergers that assembled the galaxies we observe today. For the galaxies in our sample, we hope to measure the dark matter mass fraction as a function of radius. We will learn about the dark matter content of ellipticals and bulges and search for a relationship between typical scale radii of the light and the transition to dark matter dominance.

In addition to the general trends in our galaxies, each object in our sample is associated with a merger type. NGC 1399 represents cD galaxies and other highly evolved systems. These giant objects are conglomerates of material from their clusters and they foreshadow the final state of galaxy evolution. What is the shape of a DM halo comprised of many cannibalized galaxies

¹There are notable exceptions to this including IC 2006 and NGC 4594. In some cases, HI supplies a useful value for the gradient of the potential at large radii

and their halos?

NGC 3923 has a spectacular system of 22 interleaved shells along its major axis. Unlike NGC 1399 and NGC 1316, this galaxy is in a dynamically young group, so it has evolved in a less dense environment. The simplicity of the shell system provides a valuable opportunity to explore a common feature among ellipticals. Given a straightforward merger geometry, can we identify signatures of the interaction in the PNe kinematics or the DM profile?

NGC 1316 is the brightest cluster galaxy in the Fornax cluster. It is believed to be a relatively recent merger based on its disturbed structure (Schweizer 1980) and an intermediate age globular cluster system (Goudfrooij et al. 2001). In our sample, this galaxy is the least settled and offers an opportunity to attempt to identify dynamical signatures of a merger remnant. It sits near the center of its subcluster (but far from the center of the main cluster) and it could be a juvenile cD galaxy or the dominant galaxy of an infalling group or subcluster. How does its mass distribution compare to a more evolved giant elliptical like NGC 1399?

NGC 4594 is an early-type system with a clearly-visible disk. It is conveniently oriented nearly edge-on, and it provides a comparison point between bulges and the superficially similar ellipticals. Since the disk's rotation dominates the dynamics of the visible region of this galaxy, kinematic tracers from the outer parts will provide welcome constraints on the overall mass distribution and the dark matter content. The presence of the dusty disk argues that NGC 4594 has not undergone any major mergers since the gas-rich one that culminated in the disk settling. Compared to elliptical galaxies, S0s and bulge galaxies with disks are more strongly influenced by wet mergers, and they must have experienced fewer major mergers since the disk is intact. How will the dynamics of NGC 4594's bulge compare with those of ellipticals?

Our approach is to compare a range of dynamical models to observations of the projected kinematics and light distributions for this sample of early-type systems. We can illustrate the dark matter content of the galaxies by isolating the dark and luminous components of our models. We use the measured kinematics, including dispersions from planetary nebula, to look for interesting features in the outer parts like bumps and truncations. We can learn about the merger history by comparing the orbital properties (fitted by the models) of the galaxies in our sample. The combination of observations and modeling will constrain possible formation scenarios and inform our understanding of the evolution processes of early-type galaxies.

In particular, it is the halos of these galaxies are interesting because of the constraints they provide on the content of dark matter halos and the assembly history. In order to better understand the halo dynamics, we extend our

observations to large radii using planetary nebulae as kinematics tracers. The motivation behind this work was to generate samples of kinematic tracers to use in conjunction with existing estimates for the density and the kinematics as described in §1.3. The bulk of the work was devoted to measuring PN velocities, cleaning the samples, and analyzing them. Combining the finished PN velocity catalogs with more traditional photometry and integrated light spectroscopy, we are able to provide a radially complete dynamical picture to constrain the models.

In Part I, we introduce the methods used in this research. We explain the use of planetary nebulae as kinematics tracers in Chapter 2. Chapter 3 discusses the measurement of line-of-sight velocity distributions from integrated light spectra, and Chapter 4 covers the two types of dynamical models used in this project. Part II deals with the application of these methods to a sample of four galaxies. Chapters 5, 7, 6 and 8 cover the necessary background for each galaxy, the characteristics of the PN velocity sample and the models. We explore future possibilities for the work in Chapter 10.

Part I

Observational and theoretical methods for exploring galaxy dynamics

Chapter 2

Planetary nebulae as velocity tracers

An important key to understanding the formation and evolution of galaxies is to examine the kinematics of the halo where the orbits have long dynamical timescales and the mass profile is dominated by dark matter. In disk galaxies, HI measurements generally provide line-of-sight velocities out to the edges (Rubin et al. 1977; Bosma 1978). Measuring kinematics in the outer parts of early-type galaxies is more complicated since HI measurements are usually unavailable, and the signal-to-noise of the integrated light spectra drops off before the mass profile flattens. Additionally, the simple rotation of the disk is easy to observe compared to the stellar motions of elliptical galaxies which are complicated by anisotropy.

In order to understand how the stars move in an early-type galaxy, we measure rotation, velocity dispersion and, in some cases, higher-order moments of the velocity distribution. Specifically, long-slit spectra provide measurements for the first 2-3 R_e (Kronawitter et al. 2000), multi-object spectroscopy provides line-of-sight velocity distributions out to 3 R_e (Proctor et al. 2009) and IFUs can take measurements at 4 R_e (Murphy & Gebhardt 2007; Weijmans et al. 2009). Discrete tracers like planetary nebulae provide the necessary kinematic information to examine the regions beyond these limits and learn about the formation history of the outer regions of elliptical galaxies (Hui et al. 1995; Arnaboldi et al. 1996).

The planetary nebula (PN) stage occurs at the end of a star's life when the atmosphere has been ejected and is subsequently ionized by UV radiation from the exposed stellar core. Due to the extreme rarefaction of the gas in the atmosphere, these objects emit up to 15% of their light at [OIII] ($\lambda 5007$) (Dopita et al. 1992; Schönberner et al. 2010), which allows their detection and velocity measurement out to a distance of 100 Mpc (Gerhard et al.

2005). Moreover, the PN number density traces the light in early-type galaxies (Coccato et al. 2009). Because they follow the same spatial distribution as stars, PNe provide kinematics that are directly related to integrated light measurements. Since the PNe tracer the stellar population, they can also constrain the orbital structure in the outer parts where integrated light is too faint to measure higher-order moments. We are able to use planetary nebulae as kinematic tracers out to more than $7 R_e$ for measuring the dark matter distribution and angular momentum content in the halo (Méndez et al. 2001; Romanowsky et al. 2003; Douglas et al. 2007; de Lorenzi et al. 2008, 2009; Napolitano et al. 2009; Coccato et al. 2009).

As a result of their utility, several methods have been developed for the detection and velocity measurement of planetary nebulae. The options employed in this work are detailed in §2.1. The traditional on-band-off-band detection technique is used for the NGC 4594 sample in this work and it is discussed in §2.1.1.

More recently, a number of techniques have been developed that allow detection and velocity measurement to be done in the same observing run. Méndez et al. (2001) identify PNe using narrow- and broad-band images, but then follow with a dispersed image in the same run. The velocity of each PN can be calculated from the difference between the object's position in the narrow-band frame and the dispersed frame. This technique has been applied to NGC 1344, another Fornax galaxy, by Teodorescu et al. (2005). We compare the efficiency of those observations to ours in §5.2.3.3.

A similar technique, counter-dispersed spectroscopy, was applied to the PN samples in NGC 3923, NGC 1316 and NGC 1399. In place of the narrow-band and broad-band images, a second dispersed image is taken at position angle 180° . This method is described in detail in §2.1.2.

For extremely faint samples in distant galaxies, observing the entire field through slits significantly reduces the signal from the sky. Multislit Imaging Spectroscopy involves a grid of slits that are stepped until the entire field has been spectrally imaged. These types of observations have detected samples of intracluster PNe 100 Mpc away (Gerhard et al. 2005; Arnaboldi et al. 2007; Ventimiglia et al. 2008). This method is extremely time consuming but essential for distant observations where the sky dominates.

2.1 Relevant methods

2.1.1 On-band-off-band techniques with fibre measurements

2.1.1.1 Detection

Traditionally, PNe are detected using an on-band/off-band technique (Ciardullo et al. 1989). The sky is imaged through a narrow-band filter centered at the red-shifted [OIII] λ 5007 line and then again in a broad band that does not contain any bright emission lines. PNe are too faint to detect in the broad-band image, but they appear in the narrow-band image. Foreground stars appear in both narrow- and broad-band images, so the wide filter is used to distinguish them from the PNe.

In the detection stage, a catalog is generated that includes positions and magnitudes (m_{5007}) for all the detected PNe. This allows us to optionally build a planetary nebula luminosity function (PNLF) for the galaxy. PNLFs are useful for estimating the completeness of the sample and have proved a valuable tool for measuring distances to nearby galaxies (Ciardullo et al. 1989; McMillan et al. 1993; Ford et al. 1996).

2.1.1.2 Velocity Measurement

This technique has the advantage of creating a complete astrometric and photometric catalog of the PNe in the detection phase. However, the PN velocities must be measured in a subsequent observing run leaving the data at the mercy of the weather and the time-allocation committee. After the positions are measured from the on-band image, the velocities are then typically obtained using multi-slit or fibre spectroscopy (Arnaboldi et al. 2004; Doherty et al. 2009). Instruments like 2dF on the Anglo-Australian Telescope, which was used to create the catalog for NGC 4594 discussed in Chapter 8, are effective at collecting large numbers of PN velocities. This advantage plays off the light loss from fibres or slits which present a challenge to detection-limited observations. Since the catalog already exists from the detection phase, there is the possibility of reobserving interesting or under-exposed members when using the two-stage measurement process for PNe kinematics.

2.1.2 Counter-dispersed slitless spectroscopy

Counter-dispersed slitless spectroscopy is newer technique designed to avoid the two-stage detection and measurement process. The field is imaged once

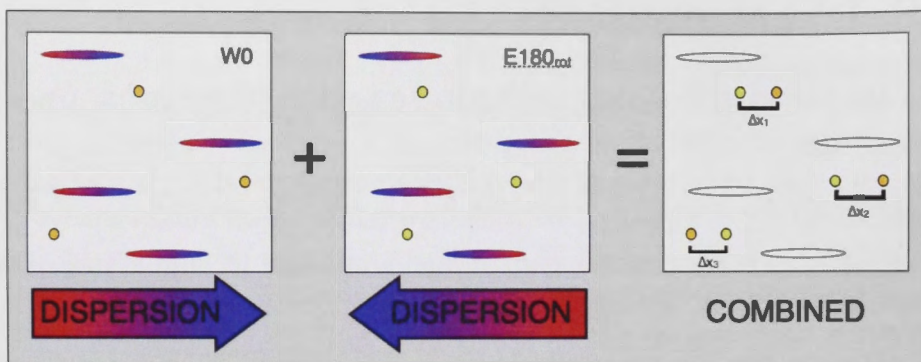


Figure 2.1 Schematic describing the counter-dispersed imaging technique. In the field shown, there are four stars (shown as rainbow continuum sources) and 3 planetary nebulae (shown as small emission-line dots). The first frame shows the W0 field with dispersion to the right. The second frame, E180_{rot}, shows the 4 stars in the same locations but now dispersed in the opposite direction. This image was taken at P.A.= 180° and rotated back during the reduction. Notice that the PN change position between these frames because of their velocity. We combine the dispersed and counter-dispersed images in the final frame by aligning the stars. The separation (Δx) of each pair of PN detections depends on the PN's velocity.

through a narrow-band filter at position angle (P.A.) 0° with a grism in the light path. This creates a spectral image where continuum sources like stars appear as streaks in the direction of dispersion. The length of the streak is set by the bandpass of the filter. Emission-line sources, like planetary nebulae appear as dots as shown in Fig. 2.1. The field is then spectrally imaged again at P.A.=180°. When this image is rotated back and registered using the stars, we see an offset in the apparent position of the planetary nebulae. This offset is a function of the PNe's velocities.

The PN Spectrograph (PN.S) is an instrument on the William Herschel Telescope dedicated to measuring PN velocities in nearby galaxies (Douglas et al. 2002). The pupil is split in half at twin gratings and the counter-dispersed images are exposed simultaneously on two cameras. A combination of the two exposures allows identification of emission-line objects and the measurement of their velocities using the separation between the positions in the two spectral images. The divided pupil has the advantage of removing effects due to variations in the observing conditions like seeing and sky brightness fluctuations.

The counter-dispersed slitless technique in this paper uses two consecutive exposures for each field to obtain positions and velocities of PNe in the

galaxies NGC 1399, NGC 3923 and NGC 1316. Because there are no slits or fibres, the light loss is reduced. The number of measurable PN velocities is not limited by the number of available fibres or the restrictive geometry of the slits. The observations for all three galaxies in this work were completed using FORS1 and FORS2 on the 8-m VLT; the large aperture makes the observations more efficient than they would be on the 4.2-m William Herschel Telescope where the PN.S is mounted.

One of the challenges of the counter-dispersed technique is registering the images and calibrating the velocities. Before rotating the exposure taken at P.A.=180° back to match the initial exposure at P.A.=0°, it is necessary to address some anamorphic distortions in the field. The distortions are introduced by having a grism in the light path and, if uncorrected, they will confuse the zero-point of the velocity calibration. A further complication is that, due to the interference filter being in a converging beam, the bandpass of the filter shifts as a function of position. This causes the apparent position of the stars to shift and, if we are to register the two exposures using the stellar positions, we must account for this. Additionally, the dispersion changes across the field. We must account for this in our measurement of the PN velocities. The details for the calibration procedure are discussed in §5.2.2.

Finally, counter-dispersed imaging comes with the risk that the detected emission-line sources are not actually PNe. For these galaxies, we can safely make the assumption that our emission-line sources are PNe, but in other cases, it would be safer to compare the object's brightness at [OIII] to H α to separate PNe from other emission-line sources like HII regions.

2.2 Alternative discrete tracers

2.2.1 Globular clusters

Planetary nebulae are not the only discrete option available for tracing the kinematics of elliptical galaxy halos. With current observing techniques, early-type galaxy surveys usually contain many more detectable globular clusters than detectable planetary nebulae (e.g. compare Dirsch et al. (2003) to McNeil et al. (2010)). The globular cluster system extends far out into the halo, probing the frontier of the intra-galactic medium. However, the globular cluster spatial distribution is, in general, flatter, and their kinematics do not trace the same population as the stars (Harris 1991; Ashman & Zepf 1998; Brodie & Strader 2006). Any tracer in equilibrium can be used to constrain the mass, but only consistent tracers can be combined.

The dominant component of the outer parts of the globular cluster sys-

tems in most galaxies is the blue part of a bimodal color distribution (Brodie & Strader 2006). The radial distribution of this component is flatter than the integrated light from the stars. However, in many galaxies, including NGC 1399 (see Chapter 5), the red globular cluster sample does follow the integrated light (Bassino et al. 2006; Brodie & Strader 2006; Schuberth et al. 2010), and we find the kinematics of this subset to be comparable to those of the integrated light and the PNe.

In galaxies where there is color bimodality, the red component matches the stellar spatial distribution and the red GCs are in equilibrium, globular clusters provide excellent kinematic constraints. We can observe hundreds or thousands of GCs in a massive elliptical and their radial limit extends well into the DM halo.

This work focuses on observations of planetary nebulae as a means of constraining the kinematics of the outer parts of early type galaxies. Where data is available, we compare our results to those from globular clusters, and even combine them in the case of modeling NGC 1399 (see §5.3.2.1).

Chapter 3

Line-of-sight velocity distributions from integrated light

Planetary nebulae are not visible in the inner regions of these galaxies because the signal from the stellar light is too strong. We can only measure their velocities in regions where a narrow-band filter cuts out enough light from the stars to make the $\lambda 5007$ emission line comparatively bright. Kinematics for the inner regions are needed to complement those from PNe in the halo, and they are essential for understanding the mass-to-light ratio and the anisotropy of the luminous matter. The most basic way to measure the line-of-sight velocity distribution is by examining the absorption lines in integrated-light spectroscopy. Each line's profile is built up as the sum of all the stellar light along that line-of-sight. The mean velocity is described by the shift of the lines, and the dispersion is calculated from the width of the lines.

This description parameterizes the line profile as a Gaussian and, therefore, assumes that the stars contributing to the galaxy light have a Gaussian velocity distribution. Furthermore, when working with discrete tracers like planetary nebulae, we are forced to approximate the velocity distribution with a Gaussian. Because our samples contain tens or, at best, hundreds of objects, we struggle to measure the higher-order moments of the distribution.

However, as you move towards the central parts of a galaxy, the integrated stellar light affords sufficient signal-to-noise to extract more information about the orbits of the stars. Rather than approximating the line-of-sight velocity distribution as a Gaussian parameterized by velocity v and dispersion σ , we hope to supplement that picture with inferred details on the skewness and kurtosis.

Conventionally, the higher order moments are quantified using Gauss-Hermite functions. These are selected on the basis that they are an orthogonal sequence for which the 0th-order term is a Gaussian and higher-order terms measure the deviation from a Gaussian (van der Marel & Franx 1993; Gerhard 1993). The full set of coefficients completely determines the velocity profile, and we can measure higher and higher order moments from our data as the signal-to-noise improves. It is common to measure up to and including the sixth moment of the velocity distribution, but we limit ourselves to velocity v , dispersion σ , h_3 and h_4 in this work. Velocity and dispersion are slightly modified from our basic Gaussian approximation for the velocity distribution. The higher order terms measure deviations from a Gaussian.

Asymmetric deviation or skewness implies rotation, and it is quantified by h_3 , the coefficient of the 3rd-order Gauss-Hermite function. Negative values of h_3 indicate that the profile has a relatively steep prograde wing compared to the retrograde wing (Bender et al. 1994). This is interpreted as an excess of stars moving slower than the local mean. We measure non-zero values for h_3 when we integrate along the line-of-sight through a rotating system.

Symmetric deviation is related to the anisotropy, and it is quantified by h_4 , the coefficient of the 4th-order Gauss-Hermite function. Positive values of h_4 are associated with peaky or triangular velocity distributions (Bender et al. 1994) and imply radial anisotropy. Face-on disks can also yield positive h_4 values (Magorrian & Ballantyne 2001). A flat-topped distribution yields a negative value for h_4 and can be interpreted as tangential anisotropy. This parameter can be helpful in breaking the mass-anisotropy degeneracy (Gerhard 1993).

Where observationally possible, higher order moments of the velocity distribution are extremely valuable for learning about the dynamics of the galaxy. The h_3 and h_4 parameters add detail to the simplified picture of a Gaussian velocity distribution. They contain information on the rotation and anisotropy of the system providing important constraints for modelling.

3.1 Gauss-Hermite Pixel Fitting Software

Several codes have been developed to fit the first four moments of the velocity distribution for integrated light spectra, including fourier-space techniques (Franx et al. 1989; van der Marel & Franx 1993; Bender et al. 1994) and pixel-space techniques (Rix & White 1992; van der Marel 1994; Bender et al. 1994; Cappellari & Emsellem 2004).

In this work, we used the Gauss-Hermite pixel-fitting code (G-HPFC) from van der Marel (1994). This technique initially fits v and σ , fix-

ing them before fitting the higher order moments. In principle, the Gauss-Hermite terms are orthogonal so the result will be the same as if all of the terms are fit at the same time. Other techniques fit the terms simultaneously, and this is an important distinction between the available codes. G-HPFC was selected because it is widely used, readily available and compatible with the format of the data.

A detailed explanation of the G-HPFC is available in the literature and online, so this section only contains a descriptive summary of the process of using this code to fit the line-of-sight velocity distribution.

3.1.1 Preparing the data

The starting point for the G-HPFC is a fully-reduced, two-dimensional spectrum of galaxy light in .imh format. The wavelength dimension must be binned in $\log(\lambda)$ space. The top row of the spectrum can contain a row of sky generated from either separate sky exposures or a range at the end of the slit. This will be subtracted later in the G-HPFC. Additionally, a template star must be observed with the same instrument, reduced in the same way as the galaxy and preferably done on the same run as the galaxy. The template star must be a one-dimensional $\log(\lambda)$ -binned spectrum in .imh format. Templates should represent the range of spectral types that generally dominate the integrated light of early-type galaxies. Late G giants to mid K giants will cover this range. It is advisable to try fitting the spectra using all possible galaxy-template permutations, but the best-guess template candidate is identified before the fitting begins.

3.1.2 Step-by-Step fitting

3.1.2.1 Preparing the template star

The first step is to prepare a range of comparison spectra. Using the task `preptemp`, each spectrum is generated by convolving the stellar template with a Gaussian. The Gaussian dispersions cover a specified range and the velocity shifts are adjusted later in the fitting step. The end product of this step is a 2-D spectrum where each row represents a different convolution of the template.

3.1.2.2 Preparing the galaxy spectrum

The galaxy spectrum is prepared for fitting using the task `prepgal`. This step gives the user the opportunity to specify the wavelength range and spatial range over which the galaxy will be fit. The wavelength range needs

to include many strong absorption lines (in our case, the lines in the region around Mg *b* at 5200Å), and it should exclude any bright sky lines that may not subtract well. The spatial range should not begin on the first pixel and should avoid any bright stars that might dominate nearby galaxy light. It is possible to mask pixels that might be contaminated by a star or a background galaxy. At this stage the sky from the top row of the 2D spectrum will be subtracted.

The galaxy preparation step also completes the spatial binning. It begins at the pixel closest to the center of the galaxy and sums outwards until it reaches the user-specified signal-to-noise ratio. The number and range of the spatial bins is determined by the range of spatial rows and the signal-to-noise chosen. The end product of this step is a 2-D spectrum where each row represents the combined spectrum of a spatial bin.

The signal-to-noise ratio is calculated in electrons using the gain and read noise. These values are used to estimate the errors in our measured values later.

3.1.2.3 Fitting the line profiles with a Gaussian

The first of the two fitting steps, `fitpixgau`, calculates the best velocity and dispersion for the galaxy. The galaxy spectrum is compared to the range of convolved templates from `preptemp`, ignoring all of the masked pixels from `prepgal`. The best fit is found by minimising χ^2 in pixel space. `Pixfitgau` requires a fit to the continuum, and the user may specify the order of the polynomial.

The output from this step includes a table with the values for χ^2 , the velocity, the dispersion and errors. It also creates a table of the parameters for the continuum fit, which will be used in the next fitting step. Optionally, `pixfitgau` will also write 2D images of the best fit for each row, the residuals and the error-weighted residuals, but these are not required as inputs to the next step.

3.1.2.4 Fitting the Gauss-Hermite moments

`PixfitGH` determines the best-fitting Gauss-Hermite moments for the Gaussian parameters from `pixfitgau`. Like the previous step, it minimizes χ^2 in pixel space and ignores the masked pixels from `prepgal`. The user may specify the highest order moment to be fit. Van der Marel emphasizes in the manual that the Gauss-Hermite functions are only orthogonal in an idealized setting. Since we are masking some pixels and continuum fitting, values for h_1 and h_2 can vary from v and σ by a few percent.

Like `pixfitgau`, the output files include a table of fitted values and 2D frames showing the best fits, the residuals and the error-weighted residuals for each spatial bin.

3.1.3 Interpreting the results

The results from the G-HPFC are comprised of velocities, dispersions, h_3 values, h_4 values, errors for each fitted parameter and χ^2 values for each bin in each of the slits. Each slit must adjust the velocities to heliocentric based on the date of observation. Each fit needs to be adjusted for the radial velocity of the template star used in the fit. Offset slits need to have an adjustment to their radial scales to reflect projected radius from the center of the galaxy.

At this stage, the results from the G-HPFC are ready for interpretation. We follow the velocity profile to understand the rotation of the system. The s-shaped curve that traditionally signifies a rotating system is likely to be reflected in the h_3 profile. The dispersion profile is expected to be high in the center and then fall as the radial density distribution decreases. A rising dispersion in the outer parts can be an indication of a dark matter halo if the mass excess is not reflected in the light. It is likely that the anisotropy will vary as a function of radius— h_4 indicates whether radial ($h_4 > 0$) or tangential ($h_4 < 0$) orbits are dominating at that location.

These four moments of the velocity distribution can be used to constrain dynamical models. By comparing a range of models to observations of the Gauss-Hermite parameters, we can better understand which formation scenarios are feasible. See Chapter 4 for more discussion of dynamical modelling.

Chapter 4

Dynamical Models

The analysis of observational data is more meaningful when it is compared to a model. We create a range of models with well-understood dynamics. By matching our observations to one of our models, we gain information about the physical situation of the galaxy in question. A successful model gives the geometry and orbital structure of the galaxy. From there, we may be able to infer something about the assembly history and present evolutionary state of the galaxy by comparing with simulations. In this work we employ two modeling methods: Jeans Models and NMAGIC.

4.1 Jeans Models

4.1.1 The Jeans equations

The Jeans Equations are Euler's equations of fluid dynamics applied to stars in galaxies. Beginning from Eqn. 4-27 in Binney & Tremaine (1987) and slightly modifying their notation, we examine the form

$$\rho(r) \frac{\partial \bar{v}_j}{\partial t} + \rho \bar{v}_i \frac{\partial \bar{v}_j}{\partial x_i} = -\rho \frac{\partial \Phi}{\partial x_j} - \frac{\partial (\rho \sigma_{ij}^2)}{\partial x_i}, \quad (4.1)$$

where $\rho(r)$ is the spatial density of stars, $\bar{v}$ is the mean stellar velocity, Φ is the total potential and σ_{ij}^2 is the dispersion which accounts for the fact that not all stars at a given location are moving at the same velocity. Summation over i in the velocity dispersion tensor term is implied.

The form of Eqn. 4.1 is helpful because it allows us to compare our model to observable quantities like the density and the dispersion of the stars. For this to be practical, we must make some symmetry assumptions about the potential. Simplifications of the dispersion tensor, σ_{ij}^2 , follow. In this thesis,

we assume spherical symmetry which simplifies Eqn. 4.1 to

$$\frac{1}{\rho} \frac{d(\rho \sigma_r^2(r))}{dr} + 2 \frac{\beta \sigma_r^2(r)}{r} = - \frac{d\Phi}{dr}, \quad (4.2)$$

where β is the anisotropy of the velocity distribution ($\beta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$).

The terms on the left-hand side of Eqn. 4.2 are related to observationally accessible quantities. Both Eqn. 4.1 and Eqn. 4.2 are volume quantities which are projected to observable surface quantities by integrating along the line-of-sight. We are able to measure the projected velocity dispersion and the surface brightness for our galaxies. We can infer a mass profile from the distribution of light (assuming a constant mass-to-light ratio, Γ) and optionally adding in a dark matter component. Using these observable quantities, we can explore the orbital structure and DM content of the galaxy by comparing our observations to a range of β and Γ values.

4.1.1.1 Qualifications

The Jeans equations deal with moments of the distribution function. Our goal with Jeans modeling is to identify a model with the same moments as the data. To this end, we make specific assumptions about the symmetry and the shape of the galaxy. We also make more subtle assumptions about the distribution function. Notably, our definition of the anisotropy assumes that $\sigma_\phi = \sigma_\theta$ because of spherical symmetry. Since our distribution function is of the form $f = f(E, \vec{L})$, we are constraining the angular momentum such that the distribution function depends on L_ϕ and L_θ in the same way.

The downside of these assumptions is that we may fit a model that is not consistent with any physical distribution function. It is possible to identify one that is not positive definite and, therefore, could not describe an actual system. Since the creation of distribution functions is so flexible, the chances of selecting an impossible model are low, but we must be aware of this shortcoming in Jeans models.

4.1.2 How to make a Jeans model

In this section, we provide step-by-step instructions for creating Jeans models. Every galaxy requires a unique model to account for differences in shape, inclination and symmetry. Moreover, not all galaxies have all the observations to constrain the models, so it is necessary to approach each galaxy individually. Das (2007) provides an excellent introduction to Jeans modeling and proved a helpful resource for this work. In this section, we describe

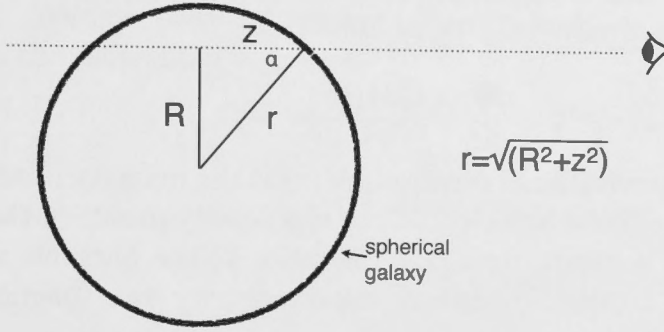


Figure 4.1 Geometry of the deprojection. The density, $j(r)$, is a function of true radius. The surface brightness, $I(R)$, is a function of projected radius. To convert from $j(r)$ to $I(R)$, we integrate along z , the line of sight.

how to fit Jeans models with constant anisotropy, constant mass-to-light and an optional dark matter halo.

4.1.2.1 Constraining the light distribution

The starting point for the model is the observed light distribution. Generally speaking, we are looking for the light density profile of the galaxy. To acquire this, it may be necessary to deproject the surface brightness profile of the galaxy. The density profile, $j(r)$, describes the density of light as a function of radius and is best expressed in $L_{\odot} \text{ pc}^{-3}$ since they are easily integrated along the line-of-sight to the distance-independent units $L_{\odot} \text{ pc}^{-2}$.

4.1.2.2 Projecting the light to the plane of the sky

In addition to the three-dimensional density distribution, it is also necessary to know the surface brightness profile of the galaxy, $I(R)$. This quantity is directly observable, but it can also be attained by projecting $j(r)$ onto the plane of the sky. This is achieved by integrating along the line of sight, z , as described in Fig. 4.1. The units can be $L_{\odot} \text{ pc}^{-2}$ or $\text{mags}/\square''$.

4.1.2.3 Estimating the total potential

The right-hand side of Eqn. 4.2 includes the total potential, Φ . We can approach Φ several ways keeping in mind that

$$\frac{d\Phi}{dr} = \frac{GM(r)}{r^2} = \frac{V_{\text{circ}}^2}{r}, \quad (4.3)$$

where G is the gravitational constant, $M(r)$ is the mass enclosed at radius r , and V_{circ} is the circular velocity. Given the density profile of the light, $j(r)$, and assuming a constant mass-to-light ratio, Γ , the baryonic mass profile, $M_B(r)$, is easily attained by integrating the density over spherical shells:

$$M_B(r) = \int_r^\infty 4\pi r^2 \Gamma j(r) dr. \quad (4.4)$$

For a self-consistent model, this form of $M(r)$ is all that is necessary for the potential. Note that the mass density, $\rho(r)$, is simply the light density, $j(r)$, scaled by the mass-to-light ratio: $\rho(r) = \Gamma j(r)$. The assumption that the mass-to-light ratio is constant with radius is contradicted by observed color gradients in early-type galaxies, but we simplify to constant Γ because the effect should not be important in the outer parts.

It's possible to add in a dark matter component, perhaps in the form of pseudo-isothermal sphere, with a mass profile

$$M_{\text{DM}}(r) = \frac{2a\sigma_{\text{DM}}^2}{G} \left(\frac{r}{a} - \arctan \left(\frac{r}{a} \right) \right), \quad (4.5)$$

where a is the core radius, σ_{DM} is the dispersion due the dark matter halo, and G is the gravitational constant. Other common forms for the dark matter distribution include alternative cored options like those described in Navarro et al. (1996) and non-cored forms like the singular isothermal sphere described in Eqn. 4-123 of Binney & Tremaine (1987).

Alternatively, the total mass of the system may be measured for some systems using hot X-ray gas (Nulsen & Bohringer 1995; Fukazawa et al. 2006; Churazov et al. 2008). This method yields the total mass profile, so it is not necessary to parametrize the dark matter halo. These observations are not available for all galaxies and, where the signal-to-noise is low, they can be associated with large errors. Moreover, recent studies of early-type galaxies (Das et al. 2011, submitted to MNRAS) show that mass estimates from X-rays can be much higher in the outer parts than estimates fitted to the data with dynamical models. It is unclear how helpful the X-ray techniques are since they yield mass estimates that are inconsistent with kinematic tracers. The technique for generating mass profiles from X-ray gas is described in detail by Das et al. (2010).

4.1.2.4 Calculating the velocity dispersion

Referring back to Eqn. 4.2, we have obtained expressions for the density and the potential. We now solve for the velocity dispersion, σ_r , by rearranging Eqn. 4.2 into the differential equation

$$\frac{d\sigma_r^2(r)}{dr} + \sigma_r^2(r) \left(\frac{1}{j(r)} \frac{dj(r)}{dr} + \frac{2\beta_0}{r} \right) = -\frac{j(r)V_{\text{circ}}^2(r)}{r} \quad (4.6)$$

with the solution (see Appendix in Das 2007)

$$\sigma_r^2(r) = \frac{1}{r^{2\beta_0}j(r)} \int_r^\infty \frac{r'^{2\beta_0}j(r')V_{\text{circ}}^2(r')}{r'} dr'. \quad (4.7)$$

Notice that we have assumed constant anisotropy, β_0 starting with Eqn. 4.6. Observational evidence does not support this simplification (de Lorenzi et al. 2009), but since we are mainly interested in the outer parts of the model, we accept the convenience and the acknowledgement that the central parts may require a slight modification.

4.1.2.5 Projecting the velocity dispersion of the model

The velocity dispersion, $\sigma_r(r)$ is not directly observable. The true dispersion is projected along the line-of-sight to give the projected velocity dispersion, $\sigma_p(r)$, which we can measure. To project the velocity dispersion of the model, we integrate along the line-of-sight (Das 2007) following the notation in Fig. 4.1 such that

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta_0 \frac{R^2}{r^2} \right) \frac{j(r)\sigma_r^2(r)r}{\sqrt{r^2 - R^2}} dr. \quad (4.8)$$

We can directly compare the projected velocity dispersion profile to our observations.

4.1.2.6 Finding the best model

We find the best model by fitting the measured values of $\sigma_p(r)$ while varying β_0 , Γ , a_{core} and σ_{DM} . We can quantify the goodness-of-fit by using a merit function like

$$\tilde{\chi}^2 = \frac{1}{N - n} \sum_{i=1}^N \frac{(\sigma_{\text{obs}}(R_i) - \sigma_p(R_i))^2}{\sigma_{\text{error}}^2(R_i)}, \quad (4.9)$$

where $\sigma_{\text{obs}}(R_i)$ is the observed velocity dispersion, $\sigma_p(R_i)$ is the model's projected velocity dispersion, N is the number of measurements and n is the number of free parameters. In the case of these models, $n = 4$. The best model will minimize $\tilde{\chi}^2$.

4.1.2.7 Notes on implementation

Jeans models are relatively simple and can be implemented using various plotting packages and programming languages. Das (2007) used the guidance in Numerical Recipes in Fortran 90 (Press et al. 1996) to implement her models. In this work, we use the Mathematica software. This work is facilitated by a language with reliable integrators that can cope computationally with nested integrals. Alternatively, it is possible to tabulate the values at each step and interpolate at the end to generate the dispersion profile.

4.1.3 Interpreting Jeans models

The physical implications of these models are somewhat limited because of the mean assumptions. A good fit gives us a lot of information about the system in question (assuming that the model corresponds to a physically possible DF). A poor fit is much less specific because an error in any one of the assumptions of spherical symmetry, constant anisotropy, constant mass-to-light and the parameterization of the DM halo would cause a difference between the models and the observations.

However, there are valuable conclusions to be drawn from the modeling process. Because radial orbits reach larger radii than tangential orbits of the same energy, we might expect to the edges of our galaxies to be more radial than the centers. If we observe the opposite effect, we can deduce that a merger geometry with a high angle-of-incidence caused energetic, tangential orbits to populate the outer parts.

In early-type galaxies, 10-50% of the mass within $1R_e$ is dark matter Gerhard et al. (2001); Cappellari et al. (2006); Thomas et al. (2007). By the time we get out to the outer parts, we expect to find that 80-90% of the matter is dark (Das et al. 2010). Based on this rough description, we expect a self-consistent model to be deficient in mass in the outer parts. Therefore, if our current understanding of dark matter distributions are correct, we expect the dispersion of a self-consistent model to be lower in the outer parts than our observations. The necessity of an additional massive component in the outer parts provides a qualitative confirmation of the importance of a dark matter halo.

Extending the idea of estimating the missing mass in a self-consistent model, we can quantify the dark matter distribution. A slightly more sophisticated Jeans Model will include a dark matter component in the mass profile (as parametrized, for example, in Eqn. 4.5) that is adjusted to improve the fit. This will improve the fit in the outer parts where the dark matter dominated the mass and it will allow a more realistic mass-to-light

ratio.

After addressing the assumed halo density distribution of the dark matter, the mass-to-light ratio and the constant anisotropy restriction, it is possible that the galaxy is still not well fit by the model. This provides an indication that our assumption of spherical symmetry is incorrect. For galaxies with strong rotation, we would not be surprised to find that an axisymmetric model gives a better fit to the observations. Generally speaking, all early-type galaxies are triaxial to some extent (Binney 1978; Bertola 1985; de Zeeuw & Franx 1991).

A spherical, self-consistent Jeans model is a good starting point for more sophisticated approaches including models with a dark component and the made-to-measure style models discussed in §4.2.

4.2 NMAGIC

NMAGIC is an adaptive N-body code with χ^2 treatment of observational errors (de Lorenzi et al. 2007). It builds on the made-to-measure (M2M) algorithm discussed by Syer & Tremaine (1996). The weight on each particle is adjusted at each step in the modeling process and the particles are allowed to evolve in the potential until the difference between the model and the observables is minimized. The adjustment of the weights is implemented by an algorithm specifying the force of change described in Eqn. 1 in de Lorenzi et al. (2007). One shortfall of basic M2M is that the measurement of the deviation of the model from the observables is too simple to account for the combination of multiple observational constraints, observables that go to zero or observational errors.

The improvement provided by NMAGIC is a χ^2 treatment of the observational errors. The difference between the model and the observables now allows for observables of varying values including zero and observational uncertainty. This improved measurement of the deviation in turn affects the force-of-change expression which ensures that the best χ^2 value corresponds to the best model.

The usual operation of NMAGIC is to allow the N particles to evolve in the potential for several thousand steps. Eventually the weights are allowed to adapt following the χ^2 M2M algorithm. When the model converges to the observations, the system is again allowed to evolve in the potential with fixed weights. Following the flowchart borrowed from de Lorenzi et al. (2007) in Fig. 4.2, the particles complete a few thousand steps of the potential solver updating their positions and velocities. Later, the χ^2 M2M algorithm in the dashed box is applied. After convergence, several steps are completed

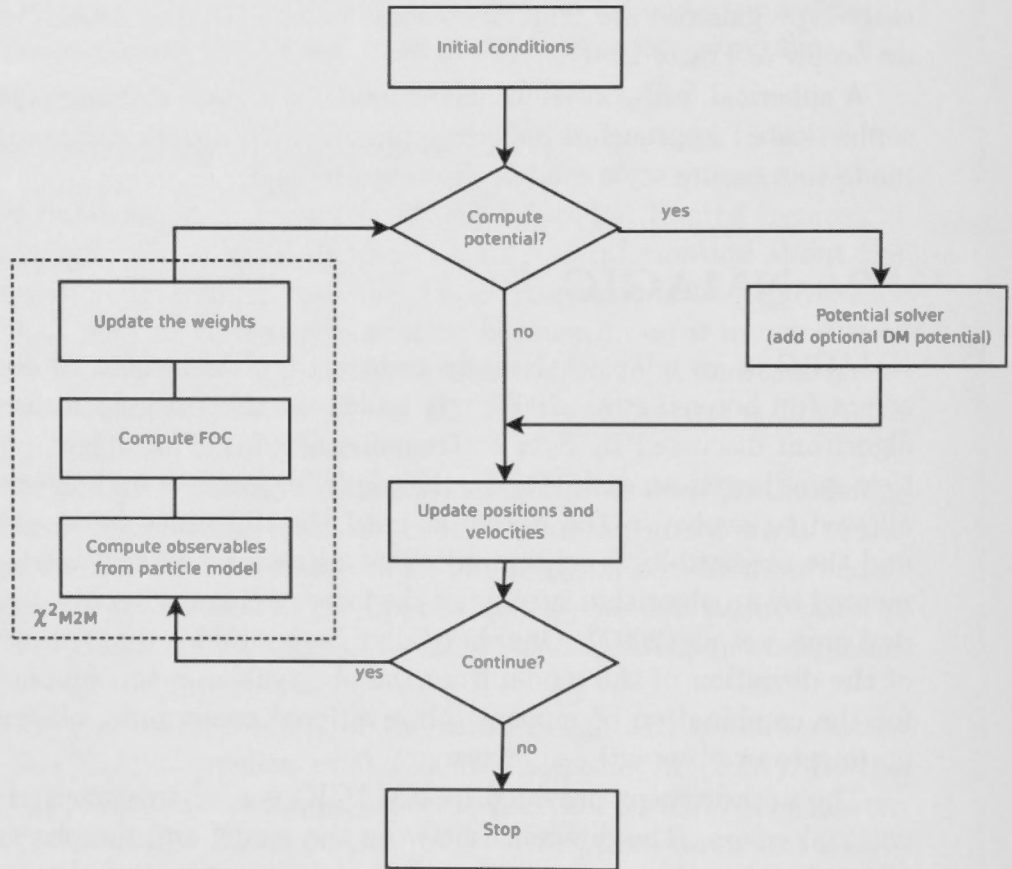


Figure 4.2 Flowchart of the operational logic of NMAGIC from de Lorenzi et al. (2007). The $\chi^2\text{M2M}$ algorithm is in the dashed box on the left. The particles generally undergo several position and velocity updates using the potential solver before having their weights adjusted by $\chi^2\text{M2M}$.

updating only the positions and velocities.

Compared to other modeling methods like orbit-library techniques (Schwarzschild 1979, 1993) and distribution-function-library techniques (Kronawitter et al. 2000; Saglia et al. 2000), NMAGIC is flexible with respect to orbit structure and overall shape. It is not necessary to specify a fixed mass-to-light ratio (as long as it is constant) for the stellar density in the initial conditions because NMAGIC evolves towards the best-fitting values. It is a useful technique for systems where ambiguities in the shape and orientation of the stellar distribution and the orbital anisotropy obfuscate the distribution of dark matter.

NMAGIC models have been successfully created for several elliptical galaxies including NGC 4697 (de Lorenzi et al. 2008), NGC 3379 (de Lorenzi et al. 2009) and NGC 4649 (Das et al. 2011, submitted to MNRAS). These models have employed a variety of observational constraints including photometry, long-slit and SAURON IFU integrated light kinematics, and planetary nebula kinematics. In Chapter 5 we will model NGC 1399 using NMAGIC constrained by photometry, long-slit spectroscopy, planetary nebulae and globular clusters. Since only one of the galaxies in this sample uses NMAGIC modeling, we will forgo a step-by-step description here in favor of a specific application to NGC 1399 later in the text.

Part II

Galaxies

Chapter 5

NGC 1399

In this chapter we cover the background, results and analysis of the PN kinematics in NGC 1399.

5.1 Background on the galaxy

NGC 1399 is a massive elliptical galaxy at the center of the Fornax Cluster. Fornax is a small cluster ($\sigma = 374 \pm 26 \text{ km s}^{-1}$, Drinkwater et al. 2001), perhaps better thought of as two groups or subclusters experiencing their first pass-through (Drinkwater et al. 2001). The brightest cluster galaxy (BCG) in Fornax is NGC 1316, located near the center of the smaller subcomponent of the cluster. However, NGC 1399 dominates its subcluster. As shown in Fig. 5.1, NGC 1399 displays the characteristic light excess in the outer halo of cD galaxies (Schombert 1986).

These objects are highly evolved stellar systems usually found in the center of clusters (Beers & Geller 1983). The light excess, often referred to as the cD envelope, mimics a diffuse light counter-part in clusters without a cD galaxy (Thuan & Kormendy 1977) and is therefore presumably a relic of the cluster formation process located at the center of the cluster's potential (Merritt 1985). Their position at the bottom of the potential and in the densest part of the cluster provides cD galaxies with plenty of opportunities to merge and evolve. Their evolved state makes cD galaxies valuable examples for understanding the formation and evolution of galaxies (Hausman & Ostriker 1978). At 20 Mpc (Tonry et al. 2001), NGC 1399 is exceptionally valuable— it is one of the closest cD galaxies, which should maximize our detection-limited PN identifications.

NGC 1399 has been well studied. The best photometry comes from HST for the central regions (Lauer et al. 1995), AAT CCD B-band photometry

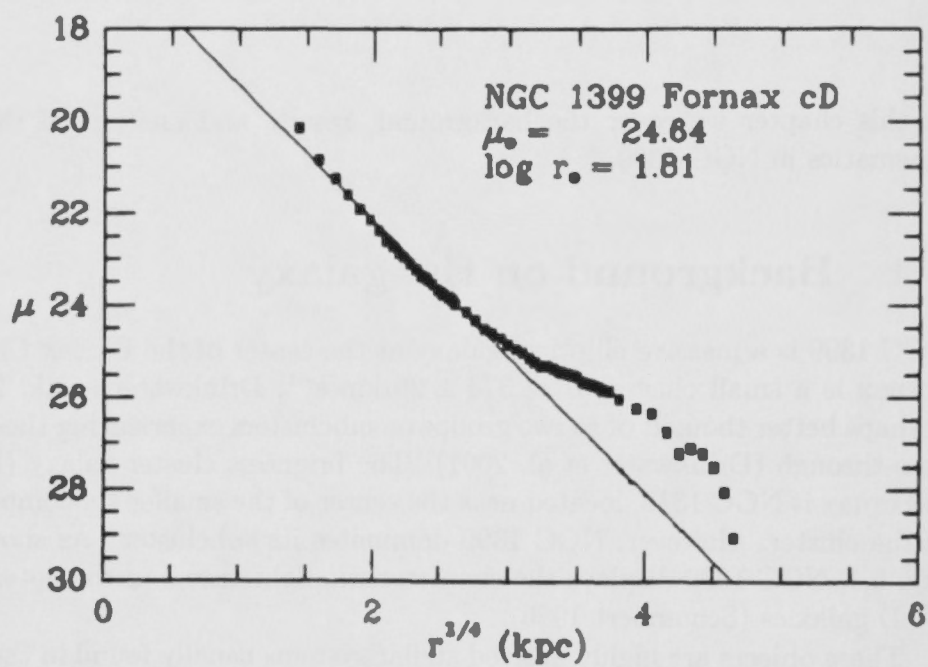


Figure 5.1 Light profile of NGC 1399 from Schombert. Notice the excess in the outer parts when compared to an $r^{1/4}$ profile.

out to $100''$ (Bicknell et al. 1989) and the CTIO Michigan Schmidt telescope for the edges (Schombert 1986). Integrated-light kinematics extend to $100''$ (Saglia et al. 2000). There is a small sample of PN kinematics from Arnaboldi et al. (1994b). Schuberth et al. (2010) provide an extensive sample of globular cluster velocities in NGC 1399.

5.2 NGC 1399 PN velocity catalog

5.2.1 Observations

5.2.1.1 Instrumental set-up

Planetary nebula kinematics observations of five fields around NGC 1399 were carried out with FORS1 (Appenzeller et al. 1998) on the 8-m VLT at Paranal Observatory during the nights of 25-27 Nov 2000. The five fields represent a subset of the 3×3 grid proposed, which was centered on the galaxy as shown in Fig. 5.2. Information from the observing log is tabulated in Table 5.1. The FORS1 field-of-view is $6'.8 \times 6'.8$ or 39.5kpc on each side at 19.95 Mpc (Tonry et al. 2001). The spatial scale is $0''.25/\text{pixel}$.

We used the 600B grating with a measured mean dispersion of $1.19\text{\AA} \text{ pix}^{-1}$. The interference filter, FILT_503.5+86, is centered near the wavelength of the redshifted [OIII] emission at the systemic velocity of NGC 1399 (1425 km s^{-1} , Graham et al. 1998). The filter, with a FWHM of $60\text{\AA}$, limits the length of the spectra of continuum sources which would otherwise cover much of the field. It allows detection of PNe with velocities within $\pm 1800 \text{ km s}^{-1}$ of the systemic velocity. For some fields, bright stars were masked out.

With this instrumental configuration, the direction of dispersion is along the horizontal axis (x -axis) depicted in Fig. 5.3. Because of the slitless technique (see §2.1.2), both axes have spatial information. In the focal plane, the presence of the grism causes an anamorphic distortion resulting in a contraction in the direction of dispersion (see discussion in §5.2.2).

5.2.2 Calibrations

The position of each PN in the dispersed image is a combination of its position on the sky, its line-of-sight velocity and the distortion from the instrument; we must quantify and separate these contributions in order to measure the velocity. The grism introduces an anamorphic distortion into the field that needs to be corrected before we measure velocities. Also, the dispersion

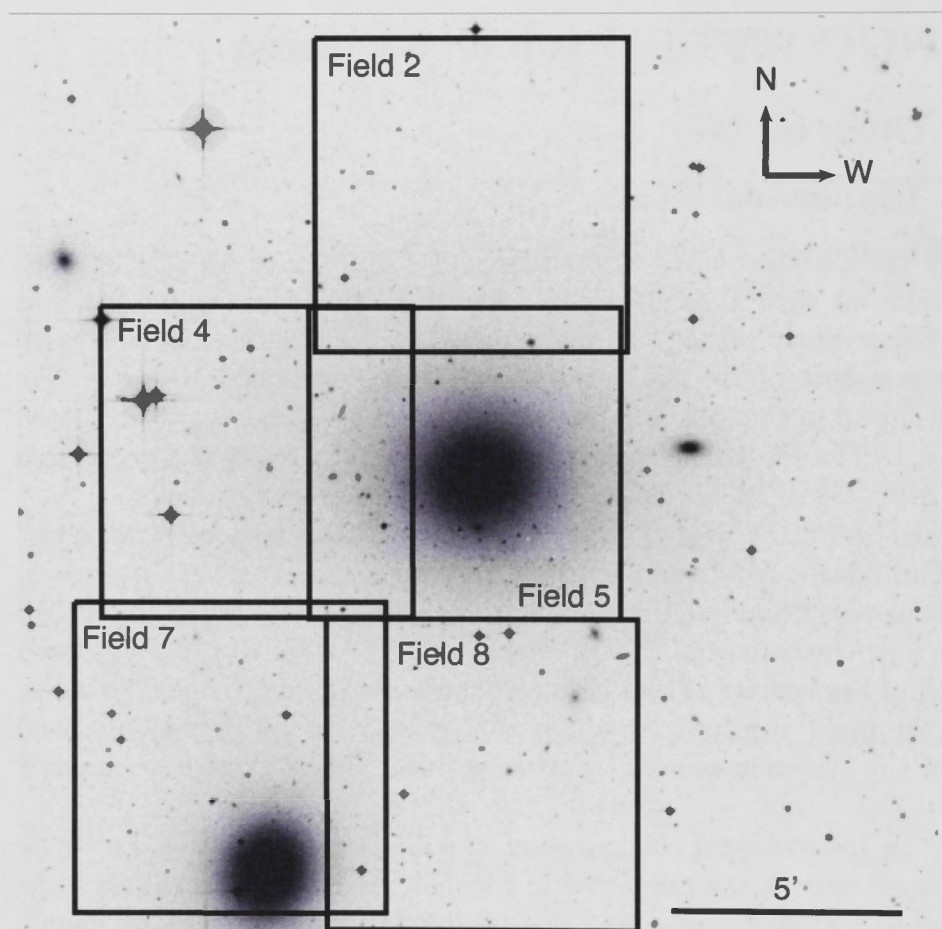


Figure 5.2 DSS image of NGC 1399 overlaid with the five observed fields. The fields were intentionally overlapped in order to confirm consistent astrometry and velocity calibration across the observations. NGC 1404 is seen in field 7.

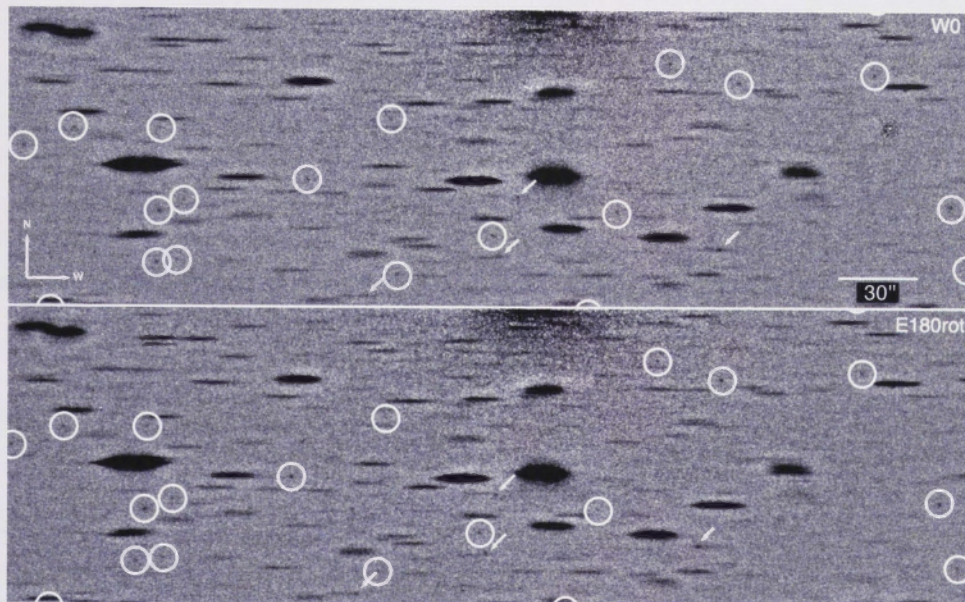


Figure 5.3 Part of the central field (field 5). The top frame is the W0 exposure and the bottom frame is the counter-dispersed E180 exposure after rotating back in the computer. The diffuse light at the top center of each frame is the southern tip of the bright central region of NGC 1399. In these images, the stars appear as streaks in the x -direction (the direction of dispersion). Examples of planetary nebula candidates are circled. Notice that there is a small difference in the PNs' x -positions in the W0 and E180 fields due to their velocity. The arrows point to emission-line objects that are associated with some continuum— these are background galaxies.

Table 5.1 Observing log for NGC 1399*.

Field	P.A. Label	Exp. Time (s)	Seeing (FWHM)
NGC1399-2	W0	3×1200	1.42''
NGC1399-2	E180	3×1200	1.34''
NGC1399-4	W0	3×1200	1.23''
NGC1399-4	E180	3×1200	1.10''
NGC1399-5	W0	3×1200	1.11''
NGC1399-5	E180	3×1200	1.09''
NGC1399-7	W0	3×1200	1.04''
NGC1399-7	E180	3×1200	1.22''
NGC1399-8	W0	3×1200	1.09''
NGC1399-8	E180	3×1200	1.10''

* Each field is observed at P.A.=0° and 180°, labeled W0 and E180 respectively.

changes as a function of position and the filter bandpass is dependent on the location in the field.

We used three sets of daytime calibration frames based on a 10×19 grid of slitlets imaged through the narrowband [OIII] filter. In the first set, the slitlets are imaged in undispersed white light. This gives us the positions of the slitlets in the grid. In the second set, the white light is dispersed. This set determines the filter bandpass as a function of position on the CCD. The final set is illuminated with a dispersed HeAr lamp. There are three lines covered by our bandpass: $\lambda 5015.67$, $\lambda 5047.74$ and $\lambda 5085.82$. This frame is used to evaluate the anamorphic distortion and to measure the local dispersion.

The daytime calibration exposures for the following steps were taken over three days where each slitlet position was exposed once in each configuration (image of the slitlet, dispersed white-light spectrum, and dispersed HeAr spectrum). The slitlets are formed by 19 pairs of moveable fingers, each calibrated at 10 positions across the field. All of the positions were co-added to create a master white-light image, a master white-light spectrum, and a master HeAr lamp spectrum. The three master calibration frames are shown in Fig. 5.4. The image processing and analysis necessary for these calibrations was done in IRAF and Mathematica. The y -position is taken to be the vertical center of each slitlet. To measure the position in the dispersion direction, 40 rows were summed along the slitlet and a Gaussian was fit—the x -position is taken to be the mean of the Gaussian. See §5.2.4.4 for a



Figure 5.4 Calibration frames. Each vertical line is comprised of 19 nearly-adjacent slitlets. Using this 10×19 grid of slitlets, we imaged the grid (left), added a grism to the light path to disperse the white light (center) and illuminated the 190 slitlets with a HeAr lamp and dispersed the light (right). In combination, these three frames allow us to map the anamorphic distortion, measure the bandpass shift as a function of CCD position and calculate the local dispersion.

discussion of how well it is possible to measure the central wavelength of the filter bandpass.

5.2.2.1 Mapping the anamorphic distortion

The first calibration step is to use the x, y -positions from the image of the slitlets in the first calibration frame and the positions of the brightest line ($\lambda 5015.67$) in the third calibration frame to map the anamorphic distortion introduced by the grism. With no distortion, the HeAr line would show a constant offset from the image of the slitlet on the CCD. We tabulate the difference in x and y and use it to make a map of the anamorphic distortion using the IRAF task `geomap`. A graphical representation of the matrix is shown in Fig. 5.5. All 190 slitlets shown were used in a 5th-order polynomial fit. Using `geotran`, we applied the solution from `geomap` to all of our images to remove the distortion.

Effectively, this transformation converts the data from the spectral into the image plane. We define the spectral and image planes like Arnaboldi et al. (2007); the spectral plane is the dispersed image as observed, and the image plane has been corrected for the distortion introduced by the grism thereby making an undispersed, distortion-corrected image for one wavelength ($\lambda 5015.67$). The PN identification and velocity measurement were done on the image-plane images because they are distortion-corrected.

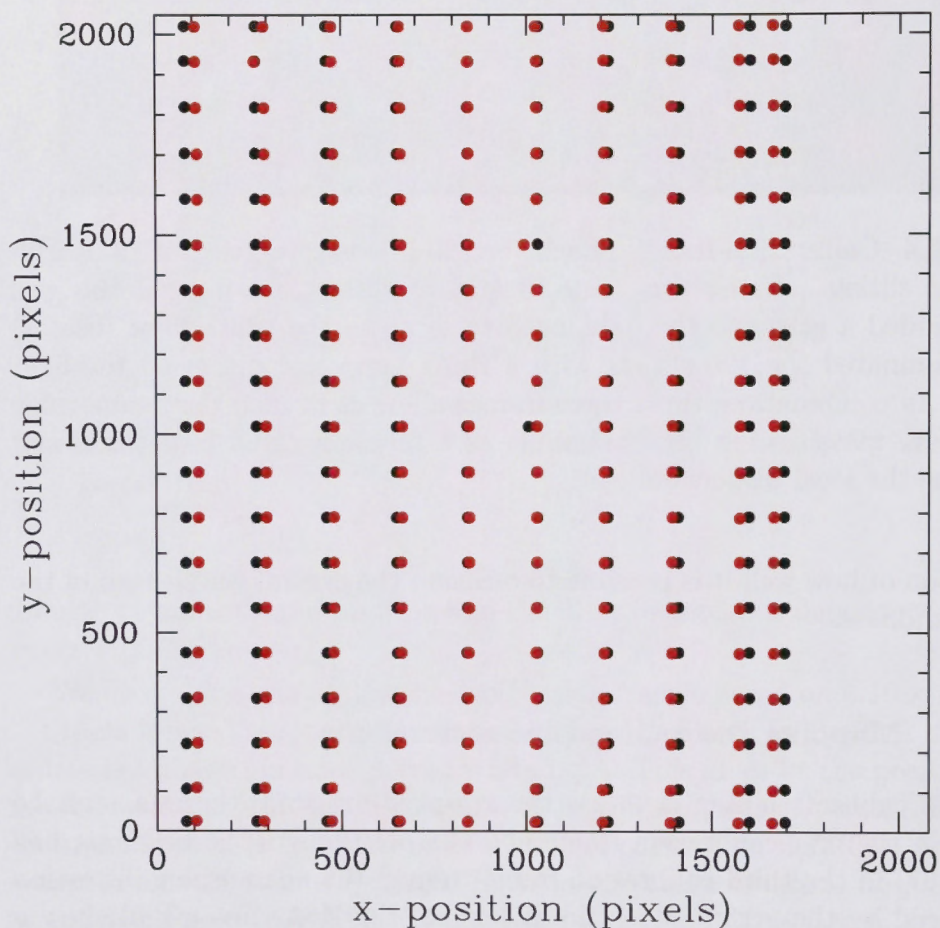


Figure 5.5 Anamorphic distortion. Each black point represents the location of the midpoint of a slitlet in the undispersed image frame. The red points are the corresponding slitlets as measured using the $\lambda 5015.67$ line in the dispersed HeAr lamp. The entire red grid has been shifted by the mean offset in order to display higher order distortions rather than the rigid shift caused by the disperser. Notice that the grism has introduced a sort of pincushion effect with the largest effects being at the right and left edges towards the middle. The two points near the center that show unexpected shifts are misidentifications, but they do not significantly affect the model of the dispersion.

5.2.2.2 Calculating the local dispersion

Next, we measure the distance between the 5015.67Å and 5085.82Å lines in the dispersed HeAr lamp image to derive the local dispersion. We assume that the dispersion is linear on this scale. The two-dimensional, 2nd-order function describing the dispersion at each of the 190 calibration slitlets is fit with **surfit**, and we interpolate to get a measurement of the local dispersion at any location.

Because we measure the dispersion in the non-distortion-corrected (spectral) calibration frame, we multiply the local dispersions by the linear term from the **geomap** solution in §5.2.2.1 when we apply them to relate position to wavelength. This is possible because the higher-order terms are small compared to the linear term of the anamorphic-distortion fit. This converts our dispersions from the measured spectral-plane dispersions to image-plane dispersions.

5.2.2.3 Measuring the bandpass shift

Finally, we map the bandpass shift as a function of position. We do this by comparing the Gaussian center of the dispersed white light to the position of the λ 5015.67 line. We expect there to be an underlying smooth, 2-D function that describes the bandpass shift caused by the presence of an interference filter at a small inclination in a converging beam. We modeled this function with a 2-D cubic using Mathematica and now we can evaluate the bandpass at any location on the CCD. Fig. 5.6 shows the measured bandpass shift across the CCD in light blue. The smooth red surface represents the model for the underlying smooth function that determines the local bandpass. The rms of the residuals is less than 0.98 pixels.

When we align the W0 and E180 images using the stars, we must first correct for the bandpass shift. In the W0 and E180 images of the same star, the light path is different causing different bandpass shifts in the two images. In general, the location of a star in our images is measured with a 2-D Gaussian using the **n2gaussfit** task in IRAF. For each star used in the alignment, we evaluate the two-dimensional cubic function at that location and apply the shift to the **n2gaussfit** coordinates. The bandpass shift is measured in the spectral plane, but we want to register image-plane images. Therefore, using **geoxytran**, we apply the anamorphic distortion correction from **geomap** to obtain the distortion-corrected bandpass-shifted location of each star. These new coordinates are used to obtain the rigid shift that will be applied to the distortion-corrected images before calculating the velocity of the PNe. Because we measure the center of the filter relative to the

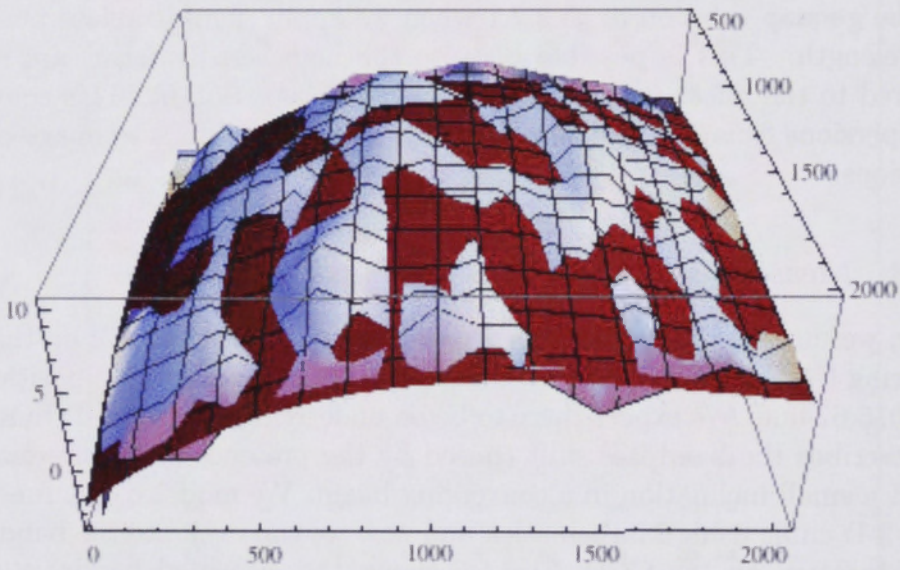


Figure 5.6 Bandpass shift as a function of position on the CCD. The shift is measured by comparing the measured center of the bandpass to the location of the $\lambda 5015.67$ -line at 190 locations across the CCD. The bumpy, blue-toned surface represents the measured shift. The smooth red surface is a 2-D cubic fit to the blue data. We evaluate the fit when correcting for this shift in the stars. All three axes are measured in pixels.

$\lambda 5015.67$ line, it becomes our fiducial wavelength. The E180 and W0 images will be aligned on the x, y positions of this wavelength in the stars, and the wavelength of the PNe emissions will be measured relative to that line.

5.2.3 Data reduction, registration and identification of emission-line sources

5.2.3.1 Data Reduction

The data reduction for the counter-dispersed technique was carried out in IRAF. Each field is imaged with three-1200s exposures at each position angle. The frames are bias subtracted and flat fielded individually. The sky flats were taken at twilight using the narrow-band filter and the grism. The three frames at each P.A. were combined using `imcombine` with a standard sigma-clipping for cosmic-ray removal.

The result is a total of 10 combined, bias-subtracted, flat-fielded frames—5 at P.A.=W0 and 5 at P.A.=E180. We subtract the background from each frame by smoothing with `fmedian` and subtracting the smoothed background from the spectral image. Next each of the frames is corrected for anamorphic distortion using IRAF task `geotran` as described in §5.2.2.1—this transforms the frame from the spectral to the image plane. We rotate the E180 image by 180° so that the stars are in comparable positions in the W0 and E180_{rot} frames; the calibration frames are no longer applicable to E180_{rot} because the direction of dispersion is opposite.

5.2.3.2 Registering the images

We must now register the W0 and E180_{rot} images in order to measure the positions and velocities of the PNe. The registration of the W0 and E180_{rot} frames is done with a rigid shift. Note that the shift is calculated from stars, which need to be adjusted for the bandpass shift as described in §5.2.2.3. More specifically, the frames are aligned on the virtual position of a set of ~ 10 monochromatic stars at $\lambda 5015.67$. To achieve this, we measure the locations of the stars in the spectral plane, apply the bandpass shift, correct for anamorphic distortion for the shifted coordinates using `geoxytran`, rotate the distortion-corrected, shifted positions from E180 only, and calculate the shift that will be applied to the images. After the registration of the frames, we can create a difference image and identify emission-line objects. The resulting pair of registered images looks like Fig. 5.3.

Table 5.2 Breakdown of emission-line objects

NGC 1399	NGC 1404	Low-vel.	Unassigned	Background
PNe	PNe	PNe	PNe	Galaxies
146	23	12	6	224

5.2.3.3 Identification of emission-line objects

In these images, emission-line sources are easily distinguished from stars because they appear as points instead of streaks. For the identification we rely on the $W0$, $E180_{rot}$ and $W0-E180_{rot}$ difference images of each field. Specifically, an object is added to the PN catalog if it is point-like in both the spatial and dispersion directions, and if it appears in both $W0$ and $E180_{rot}$ at the same y -position and with similar intensity (it need not be exact since the seeing may vary between the two images).

We identify three kinds of emission-line objects:

- Those that are point-like in both wavelength and space– these are planetary nebula candidates;
- Those emission-line sources that are associated with a continuum– these are background galaxy candidates including some Lyman- α galaxies at $z=3.1$. These objects can be either point-like or extended in the spatial direction;
- Those with resolved or double emission in wavelength. They can be extended or point-like in the spatial direction. These are also background galaxies and include some [OII] emitters.

Examples of these classes of emission-line sources are shown in Fig. 5.7. Further examples are available in Fig. 5.3. We identify a total of 411 emission-line objects in our fields. The breakdown of these detections into types of emission-line objects is shown in Table 5.2. The definitions used to distinguish members of NGC 1399 from those objects belonging to NGC 1404 and the low-velocity subcomponent are described in §5.2.4.6 and §5.2.6.3 respectively. For the planetary nebulae, we can use the known rest wavelength of the emission, $\lambda 5006.8$, to acquire the velocities using measured separation between the $W0$ and $E180$ frames– this is described in §5.2.4.1.

The efficiency of the technique: We found a total of 187 PNe in the five fields, including 146 bound to NGC 1399. As a point of comparison, Teodorescu et al. (2005) applied a related technique to NGC 1344, another Fornax galaxy, using the VLT and found 197 PNe. In their technique

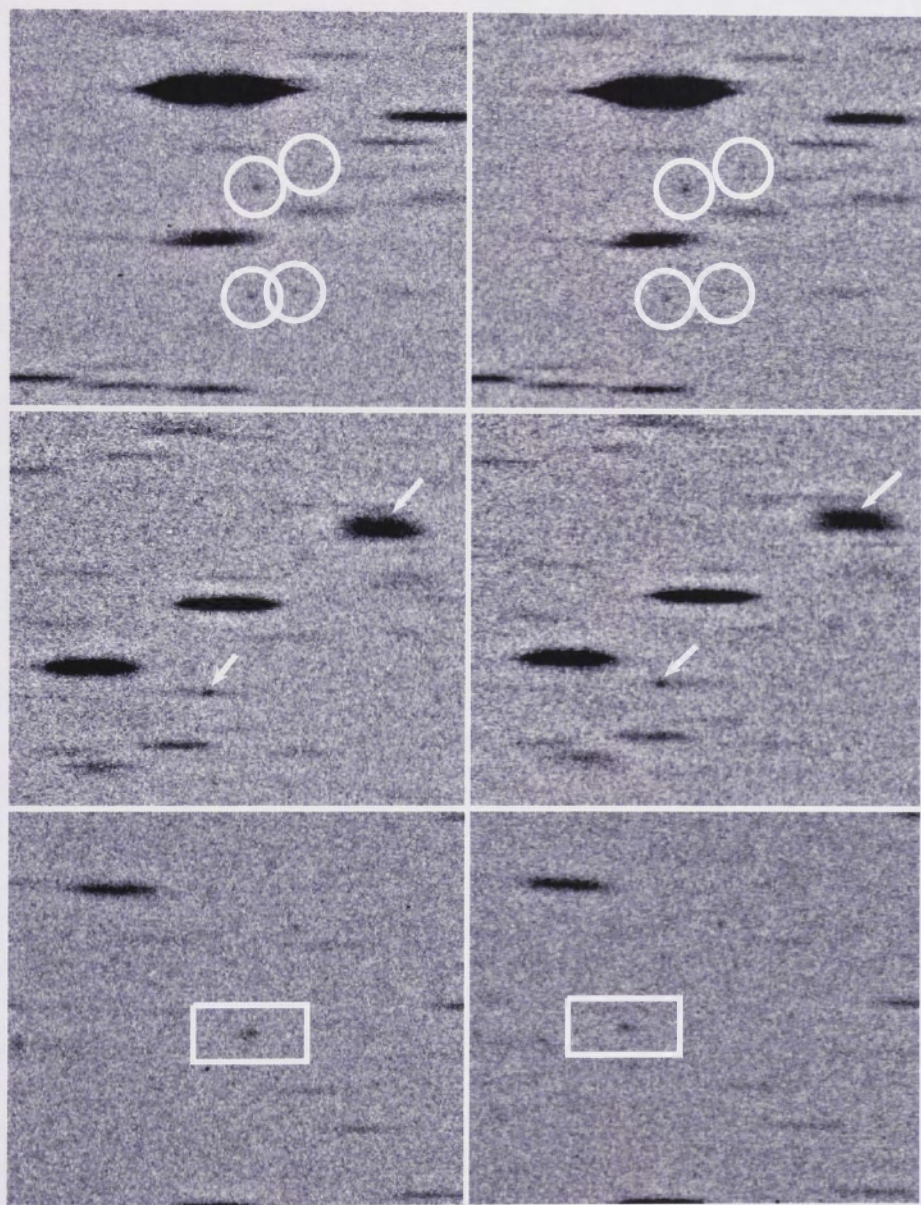


Figure 5.7 Examples of the three classes of emission-line objects identified in our sample. Each frame is 1.5 across and north is up. **top:** Four PN are circled. They are point-like in both directions. **middle:** The arrows point to two examples of background galaxies. The top-right one is a continuum source that is extended in the spatial (vertical) direction. The bottom-left one shows an emission line superimposed on some continuum. This could be a Lyman- α galaxy. **bottom:** The object in the box is slightly extended in the wavelength direction— we are seeing the double emission of an [OII] emitter.

(summarized in Méndez et al. (2001)), each field is imaged with broad- and narrow-band filters, and then a grism is added and the narrow-band image is dispersed. The velocity would be measured from the separation between the PNe in the narrow-band image and the dispersed, narrow-band image.

As elliptical galaxies in the same cluster, we expect the PN detection efficiencies in these two galaxies to scale with their color and luminosity. NGC 1399 is red compared to NGC 1344 ($B-V=0.95$ versus $B-V=0.87$ based on the extinction-corrected total luminosities published by de Vaucouleurs et al. (1991)). According to Buzzoni et al. (2006), the difference in color would indicate that the luminosity specific PN number density of NGC 1399 is 40-83%¹ of that of NGC 1344. Also NGC 1399 is almost a full magnitude brighter which should have the effect of nearly doubling the number of PN detected in NGC 1399. Finally, Teodorescu et al. covered the area around NGC 1344 uniformly, while the NGC 1399 observations only covered 5/9ths of the proposed grid. We can estimate the number of detections we are missing by symmetrizing the detections from the fields we do have. This would increase our sample by about 55 PNe.

If we adjust our detection rate for the difference in color, magnitude and coverage, we would have detected 121-251 PNe, which is consistent with the 197 NGC 1344-bound objects found by Teodorescu et al. (2005). We conclude that the counter-dispersed spectroscopy technique described in this paper provides an efficient strategy for collecting large PN velocity samples in the local volume and is comparable to the singly-dispersed imaging technique (Méndez et al. 2001; Teodorescu et al. 2005).

5.2.4 Planetary nebula velocities

5.2.4.1 Velocity calibration

The data reduction and the registration were done using the positions of the stars. As continuum sources, their spectra are approximated by the nearly-symmetrical filter curve (see discussion in §5.2.4.4) and adjusted to compensate for the filter bandpass shift. Unlike stellar continuum sources, planetary nebulae are not subject to the filter bandpass shift and their positions on the CCD are dependent on both their positions in the sky and

¹Buzzoni et al. (2006) show the luminosity specific PN number density as a function of color for a range of Local Group galaxies and external ellipticals. The two samples show different relations which result in quite different factors when we adjust for the colors of the galaxies. We assume that the relation for NGC 1399 and NGC 1344 is best described by the external ellipticals which implies that NGC 1399 sample should have only 40% of the detections in NGC 1344.

their velocities. The counter-dispersion causes each PN to appear in different places in the W0 and E180_{rot} relative to the stars (i.e. to the virtual position of monochromatic stars). This principle is illustrated in Fig. 2.1. The velocity is a function of the distance between the position of the PN in the W0 and E180 exposures and offset by the wavelength we selected for the stellar alignment ($\lambda_{5015.67}$). More specifically,

$$\lambda = \lambda_0 + \frac{d\lambda}{dx} \frac{\Delta x}{2}, \quad (5.1)$$

where λ is the measured wavelength of the planetary, λ_0 is a fiducial wavelength determined by the registration procedure (in this case, $\lambda_{5015.67}$), $d\lambda/dx$ is the local dispersion and Δx is the separation, in pixels, between the PN locations in the W0 and E180 fields.

Using this calibration, we generate line-of-sight velocity measurements for the PNe in our sample. The mean measured velocity is different from the systemic velocity of the galaxy— this indicates a zero-point offset in the calibration which is discussed in §5.2.4.4. First, in §5.2.4.2 we will determine the errors. In §5.2.4.3, we seek to demonstrate that the velocities are internally consistent and therefore represent an accurate 2-D relative-velocity field.

5.2.4.2 Errors on the velocity measurements

The individual velocity errors are a combination of the errors in reduction, registration and measurement. The total error is calculated using 17 duplicates— these are PN that are detected in the overlap region between two fields. For each set of two fields, the mean difference in the duplicates is estimated (see section 5.2.4.5) and the individual velocity errors for our sample are determined from the standard deviation of the differences between all the pairs from overlapping areas. We measure an rms in the difference of 52 km s^{-1} , corresponding to an individual velocity error of 37 km s^{-1} . This value is comparable to the 40 km s^{-1} error on the velocities in Méndez et al. (2001), but it is larger than the 20 km s^{-1} errors in the Planetary Nebula Spectrograph data (Douglas et al. 2002).

PNe in our sample range from approximately 150 to 400 counts. Assuming a Gaussian PSF (FWHM=4.7pix) for each PN, we estimate that the velocity precision is between 7 and 12 km s^{-1} . This indicates that the error of 37 km s^{-1} is dominated by other uncertainties associated with the anamorphic distortion and the varying dispersion.

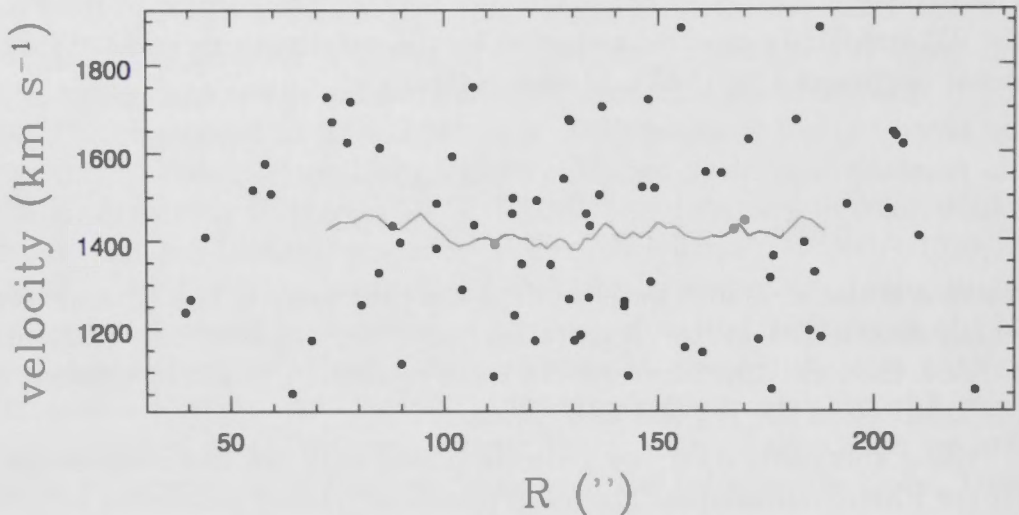


Figure 5.8 Velocity distribution of our central field’s PN candidates as a function of radius. The red line marks the running average computed with 20 PNe in an annular bin. The lack of a trend in the average indicates that the velocity calibration does not vary with radius.

5.2.4.3 Testing the internal consistency of the velocity calibration

Due to the complexity of the calibrations for counter-dispersed imaging, we seek to confirm that our velocity calibration is correct. The following three tests confirm that the velocity calibration does not depend on the distance of the PN from the center of the galaxy, the x, y position of the PN on the CCD or the velocity of the PN.

In the first test, we computed a running average of the velocity as a function of radius for the PNe in the central field (field 5). Assuming point symmetry, we expect to see a flat mean-velocity curve since the running average relies on averaged annular bins. Since it is not physically possible for the annular bins to have a velocity gradient, a rising or falling curve would indicate that our velocity calibration depends incorrectly on radius. In Fig. 5.8, we observe a flat running average, which indicates that our velocity calibration is not dependent on the distance to the center of the galaxy.

In the second test we looked for a trend in the velocity as a function of position on the CCD. We compared our velocities with those from Arnaboldi et al. (1994a) using 14 objects in common between the two samples with a mean difference of 166 km s^{-1} . We show the dependence in the difference as a function of x and y in Fig. 5.9, and we do not see a scaling with position.

The final test is the measured difference between the mean velocity of NGC 1399 PNe and the mean of the NGC 1404 candidates that we can see in field 7. If our velocity calibration were scaled with velocity, we would expect to see the difference in the means of the two galaxies scaled proportionately. Using a maximum likelihood technique we fit the PNe in field 7 with two normal distributions, one for each galaxy. See Fig. 5.10.

We see a difference of $491 \pm 55 \text{ km s}^{-1}$ between the peaks of NGC 1399 and NGC 1404. The fit shown in Fig. 5.10 finds the peaks at $1260 \pm 47 \text{ km s}^{-1}$ and $1751 \pm 28 \text{ km s}^{-1}$. This separation is consistent with the separation of the values in the literature of 522 km s^{-1} (Graham et al. 1998). The spatial selection caused by the boundaries of field 7 may influence the mean velocity of the NGC 1404 objects detected. As discussed in §5.2.6.2, NGC 1404 displays rotation; according to Graham et al. (1998) it would have the effect of lowering the velocities that we detect in NGC 1404 which would account for the slightly smaller measured separation. Our conclusion is that the velocity calibration does not change as a function of distance to the center of the galaxy, position in the field or velocity. We conclude that we are accurately measuring relative velocities with this technique. We discuss the determination of the absolute velocity in the next section.

5.2.4.4 Calculating absolute velocities

As described in §5.2.4.3, the measured instrumental velocities are relative velocities. Absolute velocities are necessary to compare these measurements with other kinematic tracers. The mean velocity of the current sample is 1197 km s^{-1} . Using a friendless outlier algorithm, we remove 12 low-velocity planetary nebulae that we believe are not virialized and therefore do not trace the mass of NGC 1399 (See §5.2.6.3). The mean instrumental velocity for the 146 PNe associated with NGC 1399 is $1250 \pm 17 \text{ km s}^{-1}$.

We compare the VLT counter-dispersed-technique velocities with the 1994 NTT multi-object-spectroscopy measurements (Arnaboldi et al. 1994a). As shown in Fig. 5.11, a comparison indicates that the offset is constant for objects in the center of the NTT velocity distribution. Relying on the 14 out of 17 objects that were detected in both samples in this range, we calculate a systematic offset of 166 km s^{-1} . The dispersion in the difference, 88 km s^{-1} , is consistent with the combination in quadrature of the errors in the

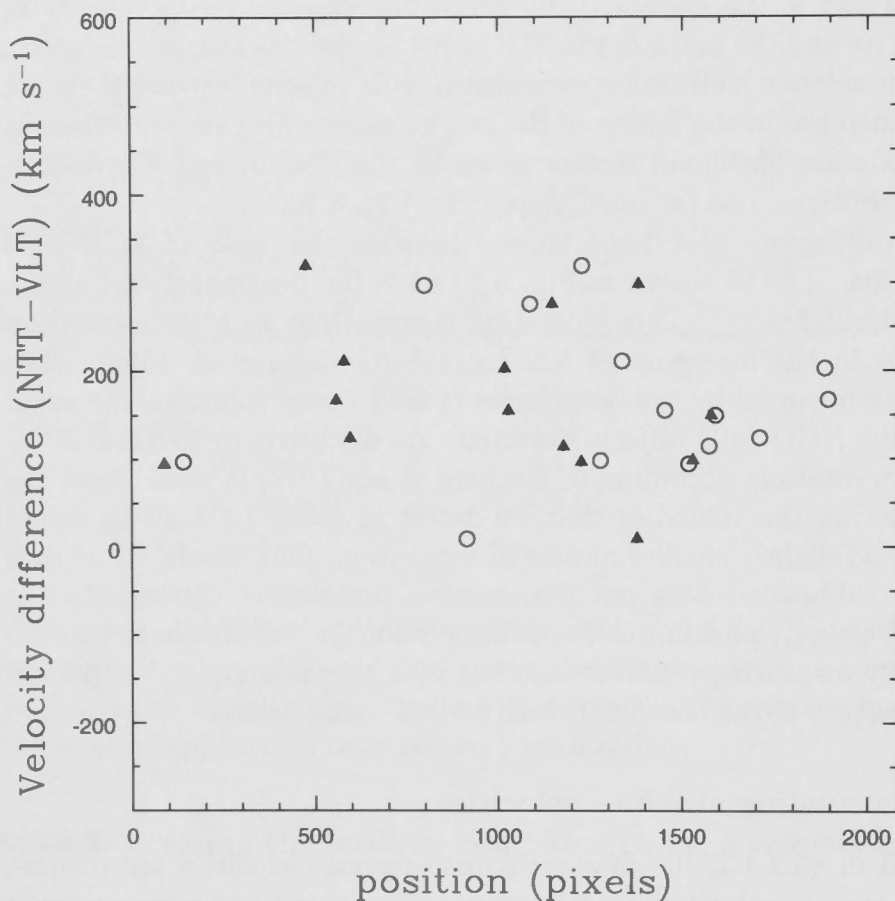


Figure 5.9 14 PNe in common between our sample and the 1994 NTT sample as a function of position on the CCD. The triangles represent the difference in velocity as a function of x -position and the open circles show it as a function of y -position. The lack of a trend in either distribution indicates that the velocity calibration is not a function of x or y on the CCD. The mean difference in velocity is 166 km s^{-1} with $\sigma=88 \text{ km s}^{-1}$. These values are addressed in §5.2.4.4.

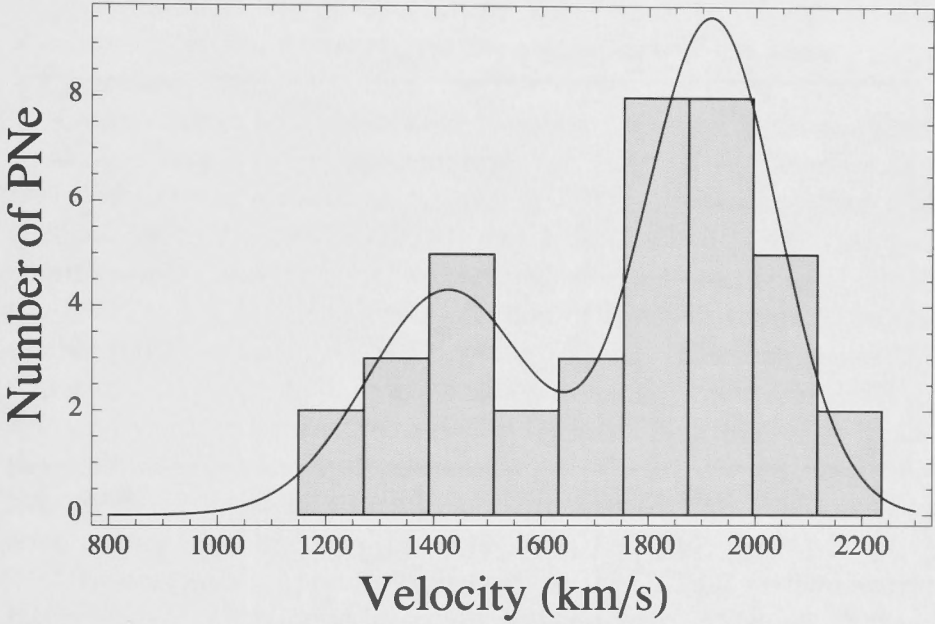


Figure 5.10 Histogram of velocities in field 7 is overplotted with the modeled velocity distribution. The model is a maximum-likelihood fit to the unbinned velocity distribution. We can compare the separation between the peaks to the difference in the published systemic velocities of NGC 1399 and NGC 1404. In this figure, we have applied the systematic shift of 166 km s^{-1} discussed in §5.2.4.4. After the shift, the fitted galaxy velocities are 1426 km s^{-1} and 1917 km s^{-1} .

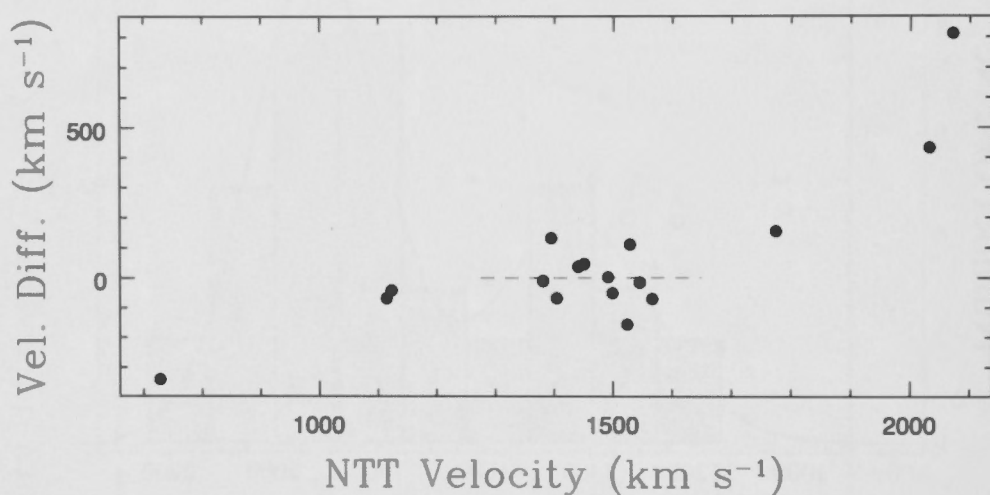


Figure 5.11 Comparison of the current velocity measurements with those from the NTT measurements (Arnaboldi et al. (1994a)). These 17 objects were detected in both samples. For the middle range of NTT values, we see a consistent agreement with the more recent data. At the fast and slow extremes, the agreement deviates. In this figure, we have already applied an offset of 166 km s^{-1} , which is the mean offset in the 14 PNe at the center of the distribution (shown with the dashed line).

VLT and NTT samples: i.e. $37^2 + 72^2 \simeq 88^2$. As the distribution in Fig. 5.9 illustrates, the offset between the previous work and this velocity calculation is not dependent on position on the CCD.

The error in the offset is calculated from the dispersion, $88/\sqrt{14} = 24 \text{ km s}^{-1}$. When we apply the shift with this error to our measured values, we find a mean velocity of $1416 \pm 29 \text{ km s}^{-1}$ for our sample of PNe in NGC 1399. This is consistent with Graham et al. (1998) where $v_{sys} = 1425 \pm 9 \text{ km s}^{-1}$ (NED) and Richtler et al. (2004) where $v_{sys} = 1441 \text{ km s}^{-1}$ for the GCs. Since the offset is constant, our measurements stand alone as relative velocities. For absolute velocities, we rely upon the adjustment of 166 km s^{-1} based on the NTT values.

Comparison to X-Shooter: X-Shooter is a new, multi-wavelength, medium-resolution, single-target spectrograph for the VLT (D’Odorico 2008). It is designed to cover a wavelength range of $\lambda 3000\text{--}24800$ using three arms: UVB ($\lambda 3000\text{--}5595$), VIS ($\lambda 5595\text{--}10240$) and NIR ($\lambda 10240\text{--}24800$). As part of the commissioning observations, we received observations of one of our PNe from the UVB and VIS arms. The resolution of $R=3640$ allows us to resolve the double [OIII] emission at $\lambda 4958.9$ and $\lambda 5006.8$. The long wavelength range and a multitude of skylines gives us a wavelength calibration with $1\text{\AA}$ precision and yielding a measured velocity for this PN of $1117 \pm 60 \text{ km s}^{-1}$. Having accounted for the systematic offset of 166 km s^{-1} discussed in §5.2.4.4, this value is consistent with the measurement of $1059 \pm 37 \text{ km s}^{-1}$ from the counter-dispersed images.

Understanding the velocity offset: In §5.2.4.3 we demonstrated that the velocity calibration is internally self-consistent. Now we discuss the systematic offset. Relative to the measurements from Arnaboldi et al. (1994a), we see a difference of 166 km s^{-1} . We explored several possibilities for the origin of this offset.

The first possibility questioned the assumption that the short stellar spectra are symmetrical in wavelength. Depending on the temperature of the star, it seemed possible that metal lines were creating an asymmetrical feature on the blue side of the stellar spectrum as seen through the filter. Our assumption of symmetry is important because we are using the locations of stars in W0 and E180_{rot} to register the images. If asymmetry caused a systematic shift of the center of the filter bandpass by say 2 pixels, it would introduce an error in the mean velocity of 131 km s^{-1} .

This issue was resolved by comparing the measured center of the filter to the measured center of a stellar template point-by-point multiplied with the filter bandpass. The centers were obtained by fitting Gaussians. The stellar templates are ATLAS9 model atmospheres with $\log(g)=4.5$, no rotation and solar metallicity (Munari et al. 2005). We covered a range of $4000\text{--}8000\text{K}$.

A typical fit to the filter and the filter-template combination is shown in Fig. 5.12. We conclude that, over this range of temperatures, the fitted center of the stellar spectrum compared to the Gaussian fit to the filter differs by less than $0.3 \text{ \AA}$ or 20 km s^{-1} and therefore the absorption lines are not the cause of the zero-point offset.

The second possibility for the cause of the velocity offset is the influence of temperature on the filter bandpass. Interference filters in convergent beams generally experience a shift of $1 \text{ \AA}$ to the blue for every 5°C drop in ambient temperature (Jacoby 1989). Since the calibration frames are taken during the day, they could have introduced a systematic shift. However, according to the condition report, the dome was climate controlled to the night temperature during the day. We conclude that the temperature did not affect the velocity measurement.

After completing the astrometry and confirming its accuracy to $0''.3$ in the dispersion direction (see §5.2.5), we recalculated the velocities using celestial coordinates. This approach cuts out the registration of the images since the astrometry is completed independently for the two frames. Additionally, the stellar astrometry confirms that we understand the geometry of each plane (W0 and E180) independently. For each PN, we obtained α, δ (J2000) in the W0 and E180 frames. After calculating the separation in arcseconds, we used the plate scale ($0.25''/\text{pix}$) from the astrometry to convert to a separation in pixels and subsequently Ångstroms using the local dispersion ($\sim 1.2 \text{ \AA}/\text{pix}$). The technique did not improve the agreement between our measurements and the 1994 NTT values.

The counter-dispersed technique is also applied to NGC 3923 and NGC 1316 in this sample. In those cases, we don't measure this systematic offset in the velocity calibration. Since the two later samples were observed on FORS2 with a more straightforward calibration technique, we infer that the offset is due to some inaccuracy arising from measuring slitlets instead of positions in the calibration frames. The exact nature of the source of the offset is still unclear.

In conclusion, we have examined several sources for the velocity offset and none of them are viable. We are unable to account for this difference between our measurements and the literature. Because we are confident that our velocities are internally consistent, we approach them as accurate relative velocities.

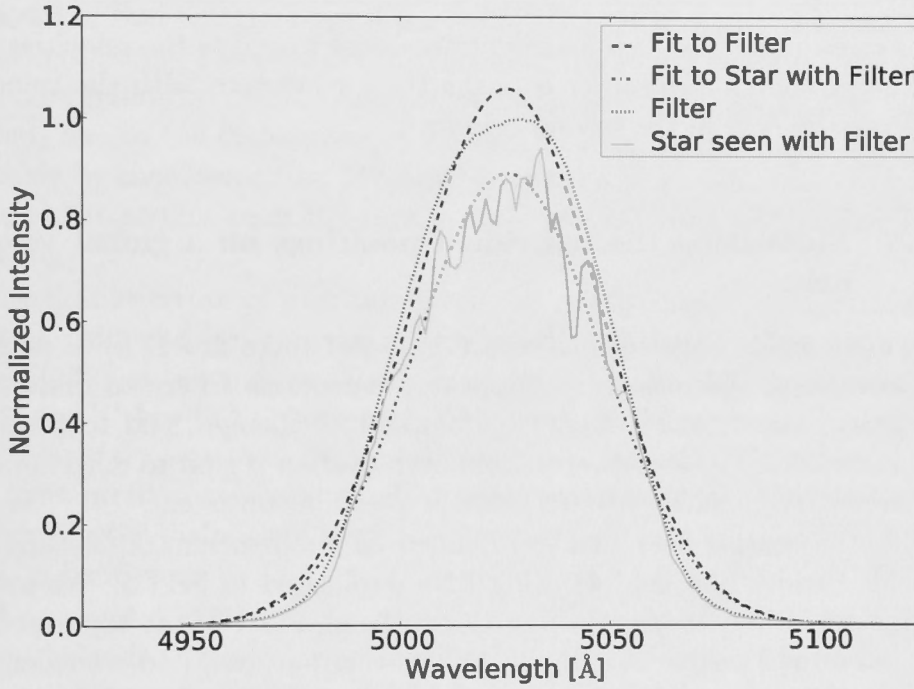


Figure 5.12 Comparison of the filter to a stellar template as seen through the filter. The filter response curve is shown as the dotted line and fit with a dashed Gaussian. The solid, gray line represents a 5500K $[\text{Fe}/\text{H}]=0$ stellar template (Munari et al. 2005) as seen through the filter. Notice the asymmetry caused by metal lines in the blue end of the spectrum. Comparing the dash-dotted Gaussian stellar fit to the dashed fit to the filter, we see that the measured position of the center will not be significantly affected by the absorption ($< 0.3 \text{ \AA}$).

Table 5.3 Duplicated detections from regions of overlap between fields

Field	Field	# of Duplicates	Velocity offset ^a
2	5	3	18 km s ⁻¹
4	5	10	-24 km s ⁻¹
7	8	3	-55km s ⁻¹
4	7	1	22 km s ⁻¹
8	phantom PNe	16	47 km s ⁻¹

^a The velocity offset is the amount necessary to add to the velocities from the first column in order to make them consistent with the velocities from the field in the second column

5.2.4.5 Mosaicking the individual pointings on a global velocity field

Some of the fields have regions of overlap, and there are 17 PNe detected in these regions. We use these duplicated detections to try to understand if the systematic velocity offset is global or if it changes field to field. We compared velocity measurements from each overlap region to determine the offset necessary to make the two fields in question consistent.

With the central field (field 5) defined as our benchmark, we adjusted two fields (field 2 and field 4) using PNe duplicated in field 5. We applied a high-sigma criterion for rejecting the outliers. Field 2, the topmost field, contained only 3 usable PN duplicates for this purpose, and we calculated an offset of 18 km s⁻¹ between the objects in field 2 and field 5. Field 4, just to the east of the central field, contains 10 duplicates, and we calculated an offset of -24 km s⁻¹ between the objects in field 4 and field 5. We apply the calculated difference to each field creating a global velocity field from the three local ones. The duplicates are summarized in Table 5.3.

The two southernmost fields do not contain reliable overlap with the fields above (see Fig. 5.2). We created a smoothed, symmetrized velocity field using the now-consistent velocities from the three known fields (see §5.2.7.1 regarding the construction of this velocity field). By assuming point symmetry of the PNe in fields 2, 4, and 5 and smoothing, we create a velocity field that covers the southern pointing (field 8). The field was evaluated at the location of 16 observed field 8 PN candidates thereby creating an equal number of phantom PNe. We then adjusted the mean velocity of the field 8 candidates to match the mean velocities of our phantom PNe by adding 47 km s⁻¹. Now, having made the field 8 velocities consistent with the rest of the field, we used 3 duplicate PNe to calibrate the velocities of the field

7 candidates, adding 55 km s^{-1} to bring them onto the same plane as fields 2, 4, 5, and 8. There is one PN in common between field 4 and field 7, but we favored the more robust adjustment to field 8 instead. This procedure ensures that the velocity measurements in all of our fields are self-consistent.

5.2.4.6 The separation of NGC 1399 and NGC 1404

As shown in Fig. 5.2, the central part of NGC 1404 is observed in the south-east field (field 7). The PNe in this field come from both NGC 1399 and NGC 1404. The published mean velocities of these galaxies differ by over 500 km s^{-1} , but, due to the dispersions, it isn't possible to separate the PNe unambiguously by their velocities. We have adopted a probability of membership method that assigns each PN to a galaxy only if it has 95% probability of belonging.

The first criterion of membership is the relative surface brightness contribution from the two galaxies at the location of the PN. The light profile of NGC 1399 is taken from Dirsch et al (2003). The light profile for NGC 1404 is an $r^{1/4}$ -law fit to photometry data from the same paper. The location of the planetary was then projected onto the major axis of each galaxy and both light profiles were evaluated at the respective radii. The ratio of flux at the projected distance of the PN is the ratio of probability of membership based on light alone.

The second criterion is the relative likelihood that an object of a given velocity belongs to the velocity distribution of NGC 1399 versus NGC 1404. The total velocity distribution of field 7 was fitted with two Gaussians through a maximum likelihood technique (Fig. 5.10). Then, reversing the technique, the relative likelihood of membership for each velocity was calculated. The ratio of likelihoods provides a ratio of probability of membership from velocity only.

Our two criteria were multiplied to produce a ratio of probability of membership value. A planetary is assigned membership if it is 19 times more likely to belong to one galaxy than the other (95% confidence interval). The 95% confidence criterion results in only 6 objects of ambiguous membership. If we lower our standard to 60% confidence of membership we would have 2 ambiguous PNe— 2 more PNe would belong to NGC 1404 and 2 more to NGC 1399. We retain the more stringent criteria. In order to examine the specific cases of the ambiguous PNe, see the figures in §5.2.6.1. The Field 7 candidates contribute 9 members of NGC 1399, 23 members of NGC 1404, and 6 of ambiguous membership. This analysis results in a total of 146 NGC 1399 planetary nebulae in our sample.

5.2.5 Astrometry

The astrometry was performed using the `imcoords` package in IRAF. We visually matched stars from USNO-B (Monet et al. 2003) to those in our images (about 10 per field). Because they are spectral images, for each star we fitted a 2-dimensional Gaussian and shifted the location to account for the local bandpass shift before building up a matrix of star positions. It is not necessary to correct for the anamorphic distortion because that transformation is folded into the mapping from the spectral plane to the celestial plane. Our images are described with a 2nd-order solution relative to the USNO-B stars. The errors on the USNO-B coordinates are $0''.2$ (Monet et al. 2003).

To check the validity of our astrometry we selected several stars that were not used in the astrometric fit and compared their calculated VLT (i.e. this sample) positions to the USNO-B coordinates. The residuals are $<0''.4$. We also completed an astrometric plate solution for a narrow-band NTT image covering roughly the same field. When we compare the NTT astrometry to the USNO coordinates, the residuals are $0''.3$ —comparable to those for the VLT data. This indicates that the spectral imagery of the VLT data does not cause an unpredictable behavior in the geometry that would affect our velocity calibration.

For each planetary nebula, we average the position in the W0 and E180_{rot} frames to get velocity-independent position coordinates. We applied the astrometric solution to these coordinates yielding an α, δ (J2000) catalog for the emission-line objects. This catalog will be included in a subsequent paper.

5.2.5.1 Comparison to X-Shooter

As discussed in §5.2.4.4, a PN from our sample was included in the commissioning data for the UVB and VIS arms of X-Shooter. The pointing coordinates for the PN were taken from the astrometric solution from the counter-dispersed images. The slit placement required a blind offset because PNe would not be visible in an acquisition exposure. As expected, the PN lands 1/3 of the way along the $10''$ -long slit. It appears very bright, so we assume that the object is well-centered on the slit. The X-Shooter observations indicate that our absolute astrometric solution is near the limit imposed by the USNO-B coordinates.

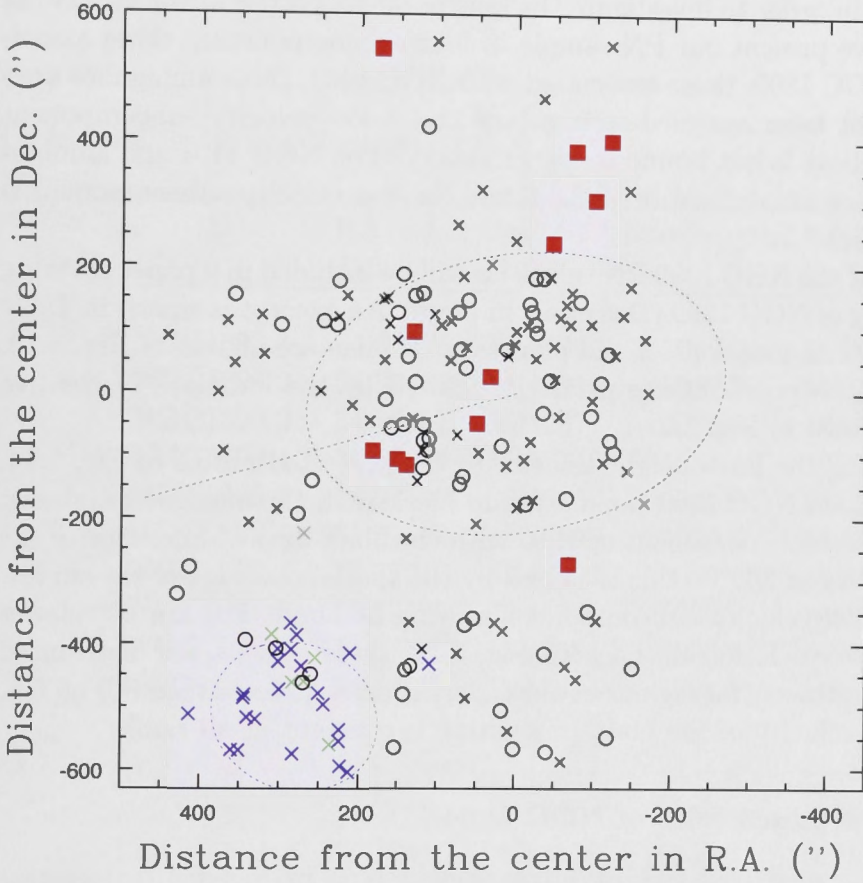


Figure 5.13 Locations of the PNe in space. PNe moving faster than the systemic velocity are marked with black crosses. Those moving slower than the systemic velocity of NGC 1399 are marked with black circles. The low-velocity objects are marked with solid red squares. Blue crosses indicate objects associated with NGC 1404 and green crosses mark the ambiguous PNe that are not assigned to either galaxy. North is up and the major axis lies at 110° (dotted line). The dotted ellipses represent the $C=25\text{mag/arcsec}^2$ isophotes based on Dirsch et al. (2003).

5.2.6 The PN velocity sample

5.2.6.1 Phase-space diagrams

In this section we view the PN 2-D velocity field in various projections in phase space in order to investigate the kinematic properties of the galaxy. In particular, we present our PN sample in four subcomponents: those associated with NGC 1399, those associated with NGC 1404, those ambiguous ones that have not been assigned to a galaxy and a low-velocity subcomponent which we believe is not bound to either galaxy. The NGC 1404 and ambiguous candidates are defined in §5.2.4.6 and the low-velocity subcomponent is defined in §5.2.6.3.

A table of the NGC 1399 PN velocities will be included in a paper covering the modeling of NGC 1399 (Das et al. in prep). An excerpt is shown in Table 7.2. The spatial locations of the planetary nebulae are shown in Fig. 5.13. Notice that the positions are primarily limited by the locations of the five pointings shown in Fig. 5.2.

Comparing the line-of-sight velocity to the projected radius in Fig. 5.14, we see the main NGC 1399 population in black with the measured systemic velocity of this subcomponent marked with the black dashed line. Notice the paucity of PNe at $300''$ —this is caused by the spatial coverage of the survey. There is a low-velocity subcomponent moving at about 700 km s^{-1} slower than the galaxy. Referring back to Fig. 5.13, these objects are distributed across the north-central regions of our observations. As confirmed in Fig. 5.8, the average velocity of the main population is constant at all radii.

5.2.6.2 PN kinematics of NGC 1404

The PNe assigned to NGC 1404 (marked in blue in Fig. 5.13) dominate the sample in the southwest. In Fig. 5.14, these objects are found at large radii, around the systemic velocity of NGC 1404 (1947 km s^{-1} ; Graham et al. (1998)). As illustrated in Fig. 5.10, the fitted mean velocity for the NGC 1404 PNe in this sample is $1917 \pm 37 \text{ km s}^{-1}$. Graham et al. (1998) report rotation in NGC 1404 that could cause the PNe that we are detecting to be up to 100 km s^{-1} slower than the systemic velocity of NGC 1404. This may contribute to the $\sim 30 \text{ km s}^{-1}$ difference between the fit shown in Fig. 5.10 and the mean velocity value in the literature.

5.2.6.3 Low-velocity subpopulation

We selected the 12 low-velocity objects from our sample using a high-sigma clipping algorithm similar to the technique in Merrett et al. (2006). It is an

Table 5.4 Catalog of PNe in NGC 1399

ID	RA J2000	Dec J2000	wavelength Å	v_{helio} km s^{-1}
NGC1399 1	54.56296	-35.45043	5032.0	1664
NGC1399 2	54.56442	-35.49913	5027.7	1412
NGC1399 3	54.56467	-35.42677	5035.6	1883
NGC1399 4	54.56946	-35.57246	5024.4	1255
NGC1399 5	54.57100	-35.40367	5031.2	1618
NGC1399 6	54.57192	-35.36103	5028.6	1482
NGC1399 7	54.57217	-35.48497	5030.2	1559
NGC1399 8	54.57425	-35.41645	5029.9	1542
NGC1399 9	54.57775	-35.43381	5028.6	1462
NGC1399 10	54.57817	-35.47684	5024.1	1196
⋮	⋮	⋮	⋮	⋮
NGC1399 144	54.76200	-35.52834	5027.9	1367
NGC1399 145	54.76746	-35.54019	5028.3	1390
NGC1399 146	54.77201	-35.42628	5030.8	1621

NOTES - Details on the astrometry are in §5.2.5. Velocities are corrected to heliocentric, shifted according to their field and corrected to the absolute velocity calibration by adding 165.7 km s^{-1} . The velocity error is 37 km s^{-1} . The full catalog will be published with the NMAGIC models of NGC 1399.

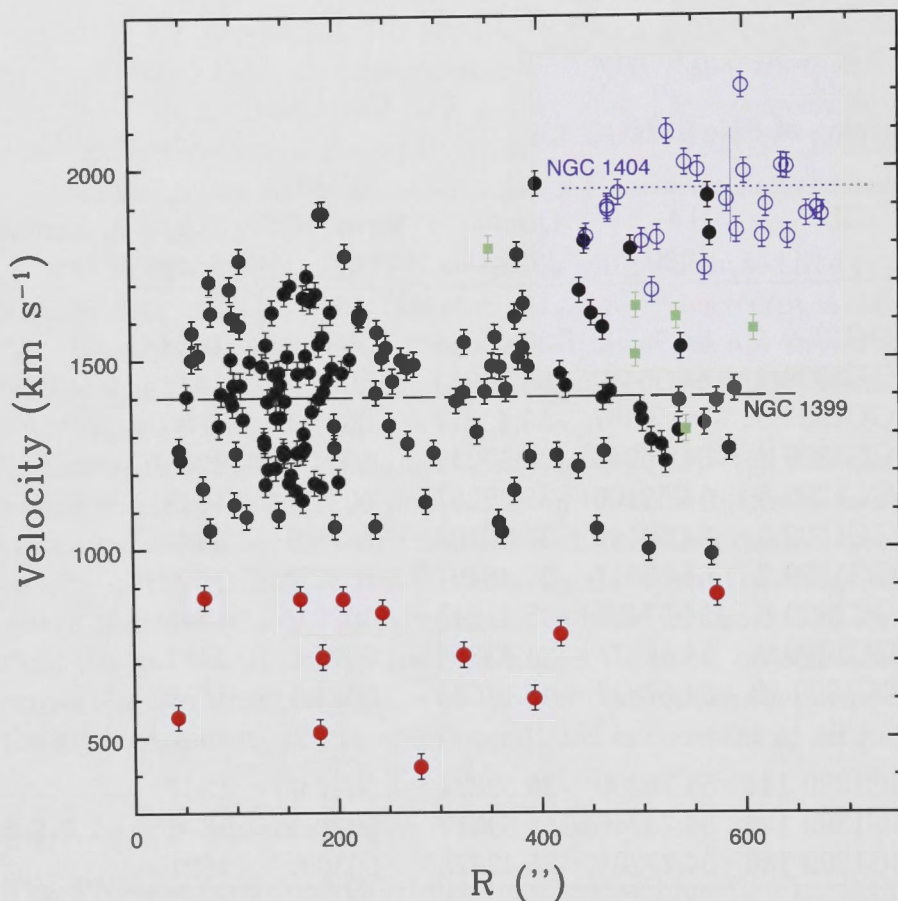


Figure 5.14 Phase space distribution. The NGC 1399 planetary nebulae velocities are shown as a function of radius in black. The 12 low-velocity objects are marked in red. The open blue circles show the NGC 1404 PNe and the green squares are those of ambiguous membership (see §5.2.4.6). The systemic velocities of the two galaxies are marked in dashed (NGC 1399) and dotted (NGC 1404) lines. The position of NGC 1404 is marked with a solid blue line at $r=588''$. Notice that a PN can be assigned to NGC 1399 based on its P.A. despite being at a radius and velocity consistent with NGC 1404.

iterative outlier test that rejects objects that lie $> 2.75\sigma$ from the mean of the total sample. The clipping limit of 2.75σ is chosen because 99.3% of a normal distribution lies within 2.75σ . In a sample of 146 objects, we expect to find less than one object outside this range. This subpopulation of 12 objects has a mean velocity of 718 km s^{-1} . Removing these low-velocity outliers symmetrizes the sample around NGC 1399's v_{sys} because there is no corresponding high-velocity counterpart.

In the high-sigma clipping algorithm, we assign PNe membership in either NGC 1399 or the low-velocity subcomponent. It is possible or even likely that one or two of the objects assigned to the subcomponent are actually members of NGC 1399. However, in most of the analysis in this paper, it is important to define the sample as a discrete set of objects, and the results will not change significantly based on the misclassification of one or two objects. This is not the case for the calculation of the velocity dispersion, which is sensitive to outliers in the wings of the distribution. The velocity dispersion calculation employs a robust fitting technique which is detailed in §5.2.7.2.

The low-velocity objects are remarkable in that they are not uniformly distributed over the entire galaxy, but rather concentrated in the north-central parts. Considering the asymmetric placement of the fields and the relatively small numbers of PNe in some of the outer fields, we considered the possibility of a selection from the filter. Because it is an interference filter at an angle in a converging beam, the bandpass function is not centered on the CCD, as shown in Fig. 5.6. We examined the 50% transmission edges of the filter as a function of distance from the intersection of the plane of the CCD with the axis of the filter, as seen in Fig. 5.15. We conclude that the filter is not causing the asymmetry in the velocity distribution. The most recent globular cluster (GC) work also shows a handful of low velocity objects in the sample removed with a tracer-mass-estimator method (Schuberth et al. 2010), which supports our claim that we are seeing a real substructure.

A low-velocity subcomponent is difficult to detect with integrated light measurements. Based on the phase-space distribution of the low-velocity PNe, we can infer that the subcomponent would manifest itself as an asymmetric feature in the line profile. This retrograde tail would be visible in the $h3$ value from integrated light measurements. Saglia et al. (2000) present $h3$ values of about -0.1 at large radii along the minor-axis slit. These measurements agree with the asymmetry in the PN distribution tending towards low velocities, but they do not provide an estimate for the amount of light or the mean velocity of the subcomponent.

The origin of the low-velocity subcomponent is unknown. The mean velocity is similar to the systemic velocity of NGC 1396 ($808 \pm 22 \text{ km s}^{-1}$, Drinkwater et al. (2001)), an elliptical galaxy to the west of NGC 1399, and

their spatial distribution is consistent with their association with the outer halo of this galaxy. Unfortunately, our observations do not extend to the west, so we lack more conclusive evidence. The low-velocity globular clusters are dominated by blue metal-poor members. This is consistent with the possibility of the low-velocity material originating from a stripped galaxy. We do not detect a velocity gradient in the low-velocity PNe, so it seems unlikely that these objects are being currently stripped as part of an interaction between the two galaxies. The photometry of NGC 1399 from the OBEY survey (Tal et al. 2009) indicates a smooth light distribution down to the surface brightness limit of $V=27.7$ mag arcsec⁻², so the stellar component accompanying the low-velocity PNe must be extremely diffuse across our fields. This corroborates the indication from the velocity gradient that we are not seeing a clearly defined stream of PNe from an infalling galaxy.

In any case, the asymmetry in the velocity distribution indicates that the low-velocity PNe are not currently phase-mixed with NGC 1399. Like in M87 (Doherty et al. 2009), we see a superposition of kinematic components in the halo of this central cluster galaxy. This reflects the complexity of galaxy superpositions and interactions in cluster cores. The subcomponents could not have been disentangled without discrete velocity tracers; having PN velocities is therefore important for deriving a complete picture of the kinematics in the outer halos of brightest cluster galaxies. The detection of subcomponents in galaxy halos is not restricted to cD galaxies. In cases like M31 or the MW, these structures can be traced with red giant branch (RGB) stars. In nearby clusters, we are unable to detect individual RGB stars, but it is possible to measure the velocities of individual PNe. Globular cluster velocities can also be used outside the local group, but we emphasize that PNe hold an important role because they are the only individual stars visible at several Mpc and they trace the stellar population directly.

5.2.7 Kinematics of the halo of NGC 1399

5.2.7.1 Rotation

Now we consider the kinematic properties of the main NGC 1399 sample. The smoothed, symmetrized velocity map shown in Fig. 5.16 illustrates the rotation in the observed fields. It is made by reflecting the entire sample (defined as the PNe which are not classified as members of NGC 1404, the low-velocity subcomponent or the ambiguous objects) in x, y and velocity and then smoothing using an adaptive Gaussian kernel smoothing as described in Coccato et al. (2009). The velocity field was fit with a cosine function in order to derive the direction and amplitude of rotation as a function of

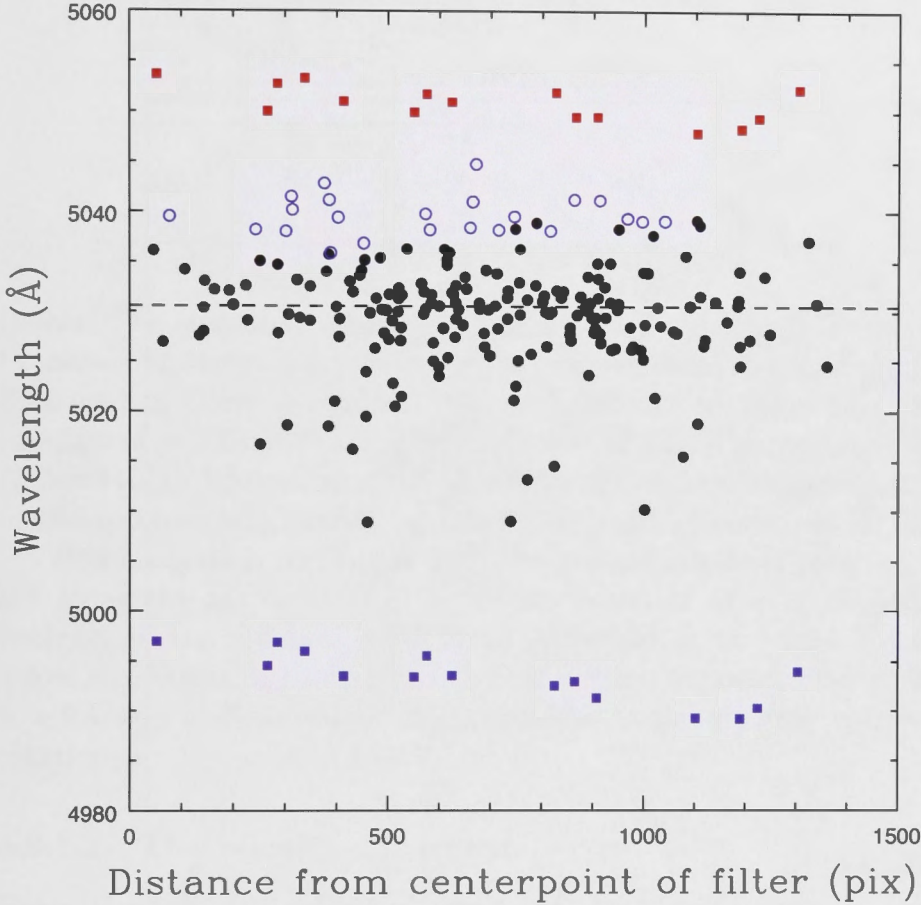


Figure 5.15 The detection limits imposed by the filter. This figure shows all of the PNe detected in our five fields. The black circles represent the ones associated with NGC 1399, the low-velocity subcomponent and the unassigned PNe. NGC 1404 PNe are marked with a blue open circle. The dotted line marks the systemic velocity of NGC 1399 (Graham et al. 1998). The red and blue squares trace the red and blue 50% transmission limits of the filter respectively. At small distances, the mean wavelength is near the mean wavelength of the galaxy. As the bandpass shifts at the edges of the CCD, the sample gets closer to the edge of the filter. Since there are no detections at or near the edge of the bandpass, we conclude the filter is not blocking the high-velocity counterpart to the low-velocity subpopulation. Moreover, we are detecting NGC 1404 PNe at these high velocities—it would be possible to see NGC 1399 ones at the same wavelength if they existed.

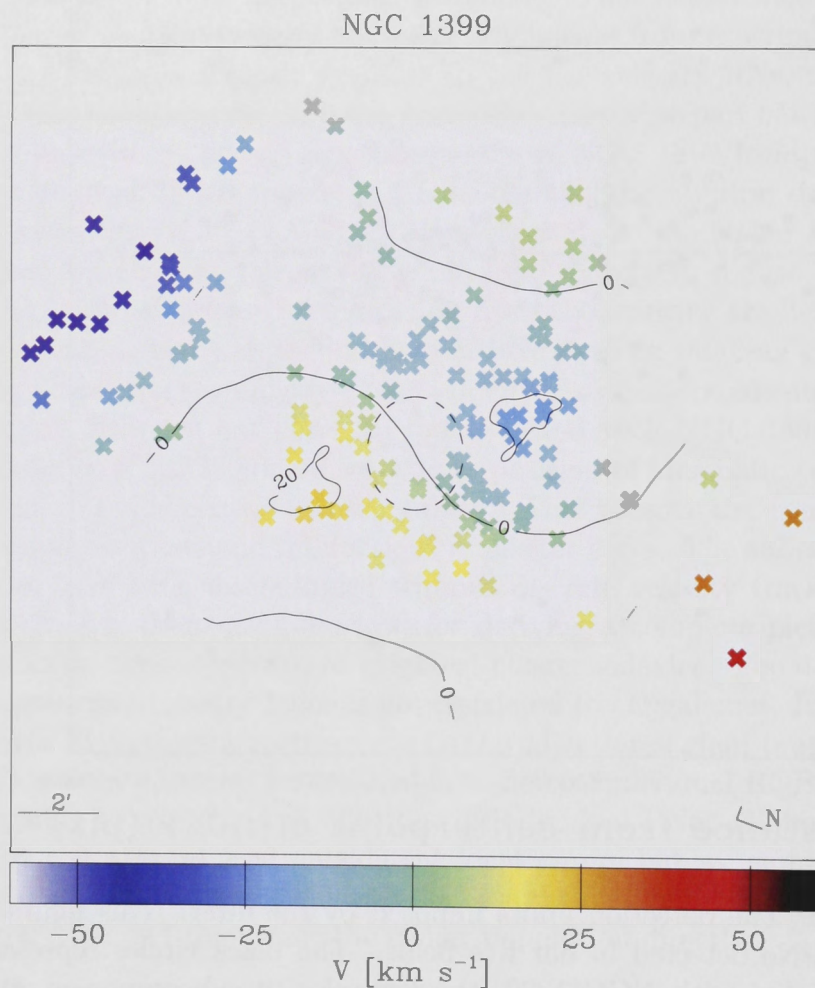


Figure 5.16 NGC 1399 halo velocities. This smoothed, symmetrized velocity map shows the location of each PN with an x. The photometric major axis is vertical in this configuration. The map indicates rotation of $\ll 50 \text{ km s}^{-1}$. The kinematic major axis is offset from the photometric major axis—the kinematic axis twists at large radii. In this figure, the 12 low-velocity PN were not included since we assume that they are not part of the dynamical system. The dotted ellipse represents $2R_e$ (Saglia et al. 2000).

Table 5.5 Rotation of the Halo of NGC 1399. The photometric major axis is at PA=110°.

Radius	# of Objects	Amplitude	Error in Amp.	P.A	Error in P.A.
"		km s ⁻¹	km s ⁻¹	degrees	degrees
60	22	15	7	233	28
200	64	20	6	246	17
400	61	20	5	339	20

radius. The measured values for these quantities and their errors (computed by means of Monte Carlo simulations) are obtained using the same process described in Coccato et al. (2009) and are listed in Table 5.5. We observe rotation of $\sim 20 \text{ km s}^{-1}$ along an axis offset from the photometric major axis (P.A.=110°). Additionally, the kinematic major axis displays a strong twist in the outer regions similar to those described in Coccato et al. (2009).

This analysis is consistent with the low-amplitude of rotation ($< 30 \text{ km s}^{-1}$ along the major axis) observed by Saglia et al. (2000) inside 1'. In contrast to the rotation result from Arnaboldi et al. (1994a), we see only a low amplitude of rotation in the outer parts— rotation of $\leq 20 \text{ km s}^{-1}$ is a fraction of their value. A comparison to the globular cluster system's rotation can be found in §5.2.7.3.

5.2.7.2 The velocity dispersion

Using the new PN velocities, we trace the dispersion out to large radii. PNe are particularly good for this task because they extend well beyond the integrated-stellar-light measurements, and their number density follows the light where they overlap (Coccato et al. 2009).

Robust Fitting: Due to possible contamination from the low-velocity subcomponent, the dispersion is calculated using a robust fitting technique. We begin by measuring the standard deviation of the data. To avoid using the tails of the distribution, we estimate the dispersion using only objects within 2 standard deviations (2σ) and then scale the measured dispersion using a factor generated in a Monte Carlo simulation of the same process. A 2σ limit is selected because we are confident that the contamination is not significant within this range. A step-by-step description of the process follows in the next two paragraphs.

Based on the number of PNe in each annular bin, 53 objects are drawn at random from a Gaussian distribution with the measured mean and dispersion of the data. Objects at greater than 2σ are rejected and the dispersion of the

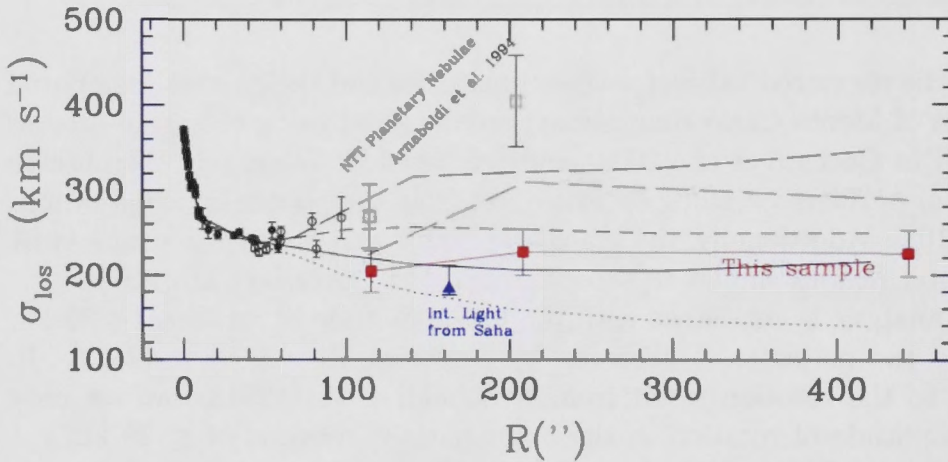


Figure 5.17 Dispersion profile of NGC 1399. The new data are shown as red squares in the outer regions. The instrumental dispersion has been subtracted in quadrature. For comparison, we have shown the calculation of the dispersions without using the robust fitting (red dashed line). The black circles represent integrated light measurements from Saglia et al. (2000) (solid=major axis, hollow=minor axis). The minor axis is projected for comparison to the major axis. The PN measurements from Arnaboldi et al. (1994a) are in green, rising steeply. The outermost integrated light point, a blue triangle, is from P. Saha (private communication), and it shows good agreement with a profile extrapolated from Saglia et al's (2000) major axis dispersion measurement and the new PN kinematics. The black lines are various models from Kronawitter et al. (2000) (see discussion in text).

remaining objects is measured. This process is repeated 10,000 times creating a Monte Carlo distribution of dispersion values. The mean of the 10,000 dispersion values is used to calculate a scaling, f_2 , between the dispersion as measured within 2σ (σ_2) and the known input dispersion (σ_{true}). We define

$$f_2 = \frac{\sigma_2}{\sigma_{true}}. \quad (5.2)$$

The dispersion of the 10,000 measurements gives the error in our dispersion values, $\sigma(\sigma)$.

Returning to the data, a 2σ limit is applied to each radial bin and the dispersion is calculated for the PNe within this limit. This dispersion is then scaled by the factor defined in Eqn. 5.3. Since we expect the initial estimate for 2σ to be influenced by the outliers, we repeat this process until the dispersion estimate stabilizes. The error, $\sigma(\sigma)$, is $f_2 \times$ the dispersion of the Monte Carlo distribution.

Fig. 5.17 shows the line-of-sight velocity dispersion as a function of projected radius calculated with the robust-fitting technique. The calculated values are included in Table 5.6. The radial limits of the bins are set such that all the bins have about the same number of objects (53 or 54). We discuss the dispersion, σ , rather than v_{rms} , but they are approximately equivalent since the rotation velocity is low. The velocity error has been subtracted in quadrature.

Comparison to previous PN measurements: In contrast to the previous measurements (Arnaboldi et al. 1994a), the velocity dispersion from the new observations is much lower and much flatter. There could be several contributing factors to this change. Compared to the 1994 values, this sample is four times larger, has more precise measurements and does not have a problem with the extreme velocities as described in Fig. 5.11. Moreover, the robust fitting treatment has a significant effect on the dispersion. This is shown as the difference between the red squares and the red line in Fig. 5.17.

In summary, this reassessment of the velocity dispersion implies a lower value than the previously published measurements. In the latest NGC 1399 data, there is no evidence of an upturn in the dispersion which would have indicated a growing influence from the cluster potential.

5.2.7.3 Other tracers

Integrated Light: The current PN dispersion values agree well with the major-axis values described in Saglia et al. (2000). One side of the parallel-to-minor-axis values does not agree well with the PN measurements, which

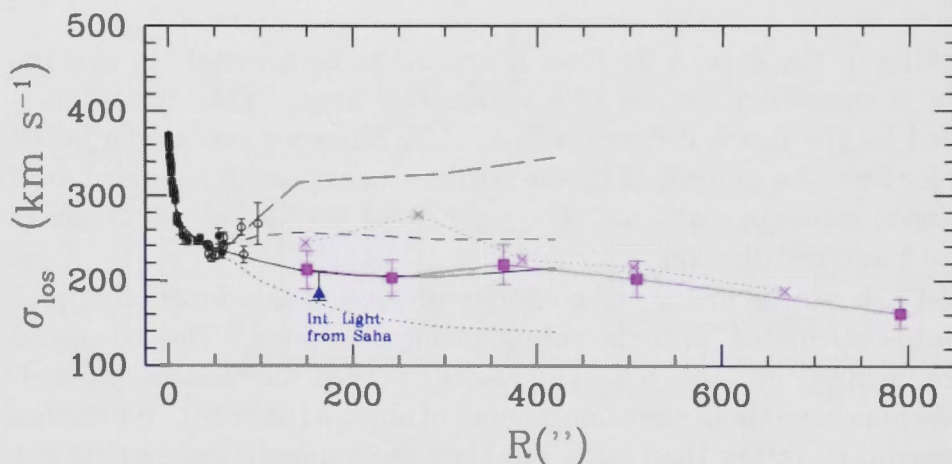


Figure 5.18 Globular cluster dispersion profile of NGC 1399. The black dots represent the same integrated light measurements described in Fig. 5.17. The magenta crosses connected with a dotted line mark the GC dispersion values from Schuberth et al. (2010). After applying the decontamination algorithm from §5.2.4.6 to Schuberth et al.'s RI sample and also removing two low-velocity GCs based on the tracer-mass estimator method in that paper, we measure the dispersions shown in magenta squares. An instrumental dispersion of 70 km s^{-1} has been subtracted in quadrature. This dispersion profile is in excellent agreement with one of the models from Kronawitter et al. (2000), as discussed in §5.3.1. Lingering contamination from NGC 1404 seems to have strongly influenced the velocity dispersion profile from Schuberth et al. (2010) around $250''$.

Table 5.6 New velocity dispersion measurements in the outer halo of NGC 1399. The radius of each bin is the mean of the radii for all the objects in that bin.

Bin	R (")	σ (km s ⁻¹)	$\sigma(\sigma)$ (km s ⁻¹)
Planetary Nebulae after robust fitting			
1	115	204	24
2	208	227	27
3	443	225	27
Revised GCs based on data from (Schuberth et al. 2010)			
1	150	224	32
2	242	215	31
3	364	230	34
4	508	214	31
5	792	176	26
Integrated Light from P. Saha (private comm.)			
–	163	184	+27/-8

suggests that there may be preferential contamination from non-phase-mixed PNe in this measurement. See Fig. 5.17.

The new PN measurements agree well with the outermost dispersion measurement from integrated light— less than 200 km s⁻¹ at 163" (P. Saha, private communication). This value, marked with a blue triangle in Fig. 5.17, is derived from one all-night, carefully-sky-subtracted, long-slit observation taken with the RGO spectrograph on the Anglo-Australian Telescope. This measurement is included in Table 5.6. Approximately equal time was spent on the target and the sky. The current PN sample is in good agreement with the largest-radius integrated light measurement confirming the consistency of these tracers.

Globular Clusters: NGC 1399 has a rich globular cluster system with about 7000 objects (Dirsch et al. 2003). Their abundance makes them potentially valuable tracers, but only the red subsample follows the radial distribution of the light and the PNe (see Fig. 15 in Schuberth et al. (2010)). We consider the velocity dispersion from the red clusters only—the blue clusters have a higher dispersion which goes hand-in-hand with their flatter spatial distribution. Although the entire GC system is moving in the same potential as the PNe and stars, the different spatial distribution of the clusters requires different kinematics if they are to be in equilibrium.

The GC dispersions included in Schuberth et al. (2010) are higher than the PNe and Saha's integrated light value. These values are shown with

magenta crosses in Fig. 5.18. The difference seems to be highly influenced by contamination from NGC 1404. The decontamination in that paper is based on a cut in radius—any objects within $3'$ of NGC 1404 were not included.

We apply the two-fold decontamination algorithm (as described in §5.2.4.6) to the red GC sample (RI in Schuberth et al. (2010)) which leads to a sample of NGC 1399 GCs that has 10 fewer objects than RIII in Schuberth et al. (2010), although some of the objects that were rejected by Schuberth et al. (2010) were kept in our sample. We also reject two low-velocity GCs from the RI sample based on the tracer-mass estimator (TME) algorithm from Schuberth et al. (2010). The GCs are rebinned to have an equal number of objects in each bin, but the dispersion values fall within one error bar if we use the bin limits described in Table A.1 of Schuberth et al. (2010). After the decontamination, the TME outlier rejection and the subsequent rebinning, the measured dispersions drop to $\sim 200 \text{ km s}^{-1}$ and are in excellent agreement with the PNe. See Fig. 5.19. The revised GC velocity dispersion values based on the two-fold decontamination are included in Table 5.6.

The globular cluster rotation analysis is summarized in §7 of Schuberth et al. (2010). In agreement with the PNe, they find marginal rotation for the red sample. The red globular cluster rotation is $61 \pm 35 \text{ km s}^{-1}$ at an azimuthal angle of 154 ± 33 degrees, but a rotation of this amplitude could be measured from randomized data with probability 27% — this is interpreted as insignificant rotation. They find rotation of $110 \pm 53 \text{ km s}^{-1}$ at $\Theta_0 = 130^\circ \pm 24^\circ$ in the blue sample, but we do not expect the blue GCs to agree with the rotation of the PNe and the integrated light based on the spatial distribution and kinematics shown in Figs. 14 & 15 of Schuberth et al. (2010). While there is disagreement about the position angle, the planetary nebula and globular cluster kinematics agree that the amplitude of any rotation in NGC 1399 would be small.

Fornax cluster galaxies: Just as PNe and globular clusters can be used to trace the mass distribution of a galaxy, cluster members allow us to estimate the cluster's mass. NGC 1399's position at the core of the Fornax cluster leaves open two possibilities for the dispersion profile at extremely large radii; the halo of a cluster's central galaxy could be dynamically separate from the cluster, or it could be part of it. For example, in the case of the Virgo cluster core, M87 displays a truncation at 160 kpc, where the velocity dispersion of the galaxy drops below 80 km s^{-1} (Doherty et al. 2009) while the potential determined from the X-rays is already dominated by the cluster mass distribution, implying that the central galaxy is dynamically separate from the cluster. If a central galaxy is not truncated, then it may be difficult to define the boundary between the galaxy and the cluster since the velocity dispersion of the galaxy could rise with radius to become similar to that of

the cluster.

Photometry of NGC 1399 from Schombert (1986) indicates that there is no truncation, at least in the stellar mass, up to a radius of about 300kpc. The component of the Fornax cluster centered on NGC 1399 has a dispersion of 370 km s^{-1} (Drinkwater et al. 2001). As discussed by Drinkwater et al., the dwarf galaxies in Fornax constitute a distinct population with a much higher dispersion than the giants ($429 \pm 41 \text{ km s}^{-1}$ compared to $308 \pm 30 \text{ km s}^{-1}$). Fig. 5.19 shows the velocity dispersion for likely Fornax Cluster members taken from Ferguson (1989). These values agree very well with Drinkwater et al. The most distant dispersion measurements of NGC 1399 available come from the GCs– the profile seems to be falling at $1000''$ (Schuberth et al. 2010). At $\sim 2000''$, the dispersion profile is not well understood. Bergond et al. (2007) see an indication of the onset of the cluster potential (Bergond et al. 2007), but Schuberth et al. (2008) interpret the same data as being part of the NGC 1399 system with a falling dispersion profile. Current observations do not bridge the space between the last GCs ($\sim 2000''$) and the first dispersion estimate from the cluster members at nearly $3000''$. At the radial limit of our sample ($500''$), the PN dispersion reaches 220 km s^{-1} indicating that these PNe are not in the regime dominated by the cluster potential, but still within the NGC 1399 halo. Mass models based on ASCA and Rosat X-ray data (Ikebe et al. 1996; Paolillo et al. 2002) indicate that the transition to the cluster potential might be at around $500''$. However, these mass models may not be consistent with the globular cluster kinematics (Schuberth et al. 2010); this issue requires more work.

5.3 Dynamical Models

5.3.1 Comparison to existing models

Here we compare the data briefly to a range of models from Kronawitter et al. (2000). These models were constructed assuming spherical symmetry based on absorption-line kinematics reaching $100''$ (Saglia et al. 2000). The anisotropy of the orbit distribution was constrained by line profile shape measurements inside $80''$. Best-fitting distribution functions were constructed in a sequence of potentials including that of the stars with constant mass-to-light ratio and an additional logarithmic halo potential. Best fit composite potentials and confidence regions were determined from the combined fit to all the absorption line data.

The lines overlayed on Fig. 5.17 represent several of the models from Kronawitter et al. (2000); note that that their projected velocity-dispersion

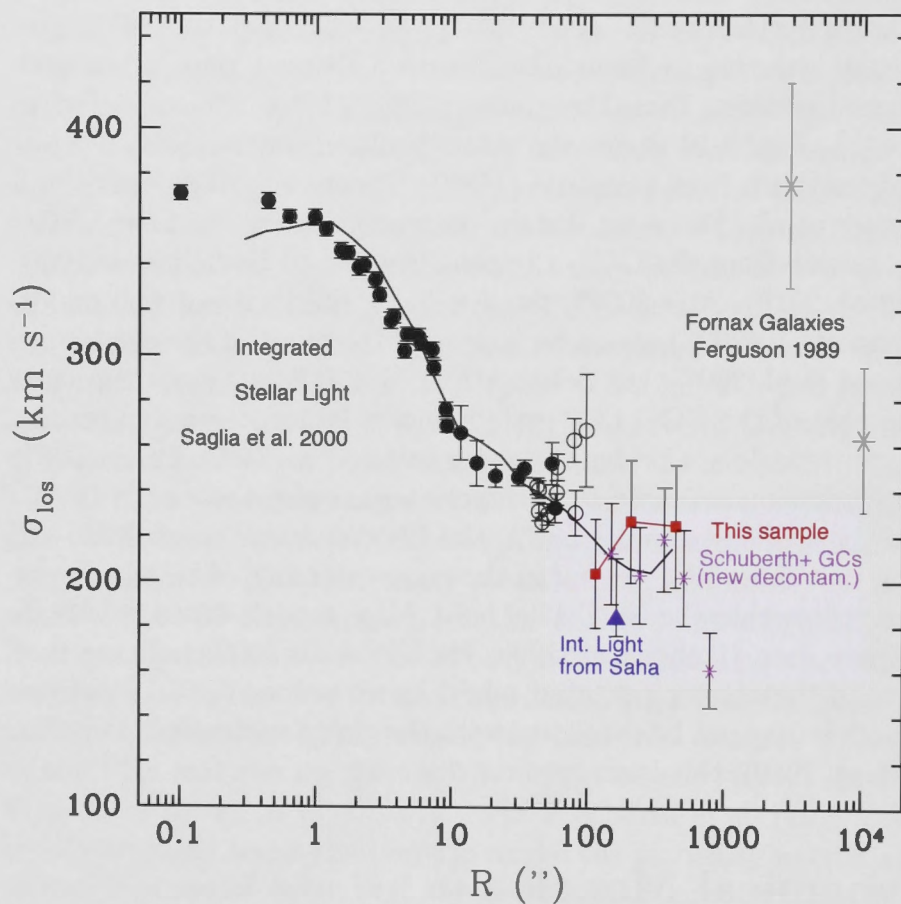


Figure 5.19 Dispersion profile representing the best values for each type of tracer. As in Fig. 5.17, the new PNe data are shown as red squares and the black circles represent integrated-light measurements from Saglia et al. (2000) (solid=major axis, hollow=minor axis). The last integrated-light measurement (blue triangle) agrees well with the new PNe dispersions. For comparison, the red GC sample from Schuberth et al. (2010) has been decontaminated with the same technique as the PNe and is displayed with magenta asterisks. The black asterisks represent Fornax Cluster dispersions (Ferguson 1989). The solid line shows the best model for the PN data from Kronawitter et al. (2000).

profiles are available only to $R = 420''$. The long-dashed model at the top represents the best fit to the photometry and integrated-light kinematics described in Saglia et al. (2000). At the bottom, the dotted line shows a self-consistent model with constant mass-to-light ratio. The short-dashed line near the middle shows an intermediate model that is consistent with the inner integrated light data as well as the outer-most PN point.

The best match to all of the velocity dispersion points from the current PN sample and also to the globular cluster points for $R < 400''$ is provided by a model at the low-mass end of the Kronawitter et al. (2000) confidence range, shown with a solid line in Figs. 5.17, 5.18 & 5.19. This line represents the velocity-dispersion profile of a mildly radially anisotropic ($\beta \simeq 0.25$) spherical model with a central B-band mass-to-light ratio of $M/L_B = 12$, a dark matter halo with circular velocity $v_c \simeq 340 \text{ km s}^{-1}$ for $R > 200''$ and a mildly increasing M/L_B -profile, reaching $M/L_B \simeq 27$ at $R \simeq 800''$ (see Fig. 5.20). Outside $100''$ the anisotropy of this model is not necessarily a good approximation for the halo of NGC 1399, however, because of the shallow luminosity density profile the velocity dispersions are insensitive to anisotropy (Gerhard 1993; Churazov et al. 2010). Nonetheless, this model is only indicative; the more-detailed dynamical modeling in the next section will explore a larger range of anisotropy and mass profiles consistent with the new data.

5.3.2 NMAGIC models

NMAGIC is an N-body code for finding the intrinsic phase-space distribution of the stars in a galaxy (see §4.2). NGC 1399 joins the list of ellipticals modeled with NMAGIC: NGC 4697 (de Lorenzi et al. 2008), NGC 3379 (de Lorenzi et al. 2009) and NGC 4649 (Das et al. 2011, submitted to MNRAS). The model for NGC 1399 is an axis-symmetric model constrained by photometry, integrated light kinematics and a combined sample of globular clusters and planetary nebulae in the halo (see Das et al. (2011, in prep) for more information about the combination of the sample).

The galaxy is represented by a set of particles where each particle is described by its 6-D phase-space coordinate and a weight. The particles' orbits are acted on by a gravitational force to update their positions and velocities while the particle weights are adjusted to minimize the difference between the observations and the model. The goodness-of-fit is quantified by a merit function, F , which is a sum over the entropy of the system, various χ^2 terms measuring the deviation of the model from the density and kinematic observables and, if required, a likelihood term that measures the agreement between the model and velocities of discrete tracers like PNe. The change in

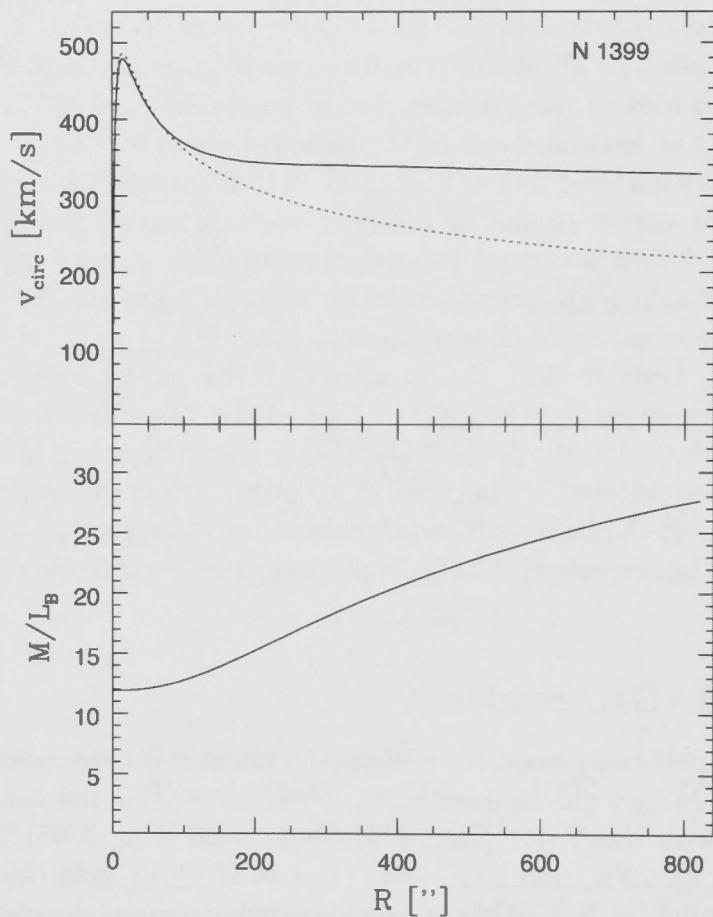


Figure 5.20 **top:** Circular velocity curve for the model from Kronawitter et al. (2000) that best fits the inner absorption line kinematics, the PN velocity dispersions and the red GC velocity dispersions (solid line). This corresponds to the model shown with a solid line in Figs. 5.17 and 5.18. The dotted line shows the circular velocity curve of a constant mass-to-light ratio model. **bottom:** B-band mass-to-light ratio profile for the best-fit model.

the weights is determined by the force of change (FOC) described in Eqn. 1 of de Lorenzi et al. (2007).

The NMAGIC modeling of NGC 1399 was completed in partnership with P. Das ². The results of the modeling are presented in Das et al. 2011 (in prep). Reproducing the discussion from that paper in sections 5.3.2.1, 5.3.2.2, 5.3.2.3 and 5.3.2.4, we describe how to prepare the observational constraints, how to set up the initial particle model, how to specify the forces acting on the stars and how to interpret the models.

5.3.2.1 Preparing the observations

Photometry. We will be fitting the luminosity density of the system so it is necessary to deproject the surface brightness measurements (Lauer et al. 1995; Bicknell et al. 1989; Schombert 1986) using the code of Magorrian (1999). This code finds a smooth axisymmetric density distribution that is consistent with the observed surface-brightness distribution for an assumed inclination ($i = 90^\circ$ in this case) by maximizing a penalized likelihood.

To verify the accuracy of this technique, we reproject the deprojection and compare it to the input. The surface brightness and ellipticity profiles are shown in Fig. 5.21. The reprojections fit the input observables very well. In the very center, the observed ellipticity profile is not well defined because the isophotes become circular as a result of the seeing. The reprojection of the ellipticity profile appears somewhat bumpy in the outerparts.

We model the deprojected luminosity density as a spherical-harmonic expansion specified by the A_{lm} coefficients (de Lorenzi et al. 2008). The model density is fit on a grid of 60 radii between $1''.5$ and $3100''$. The outer limit must extend at least 3 times further than the kinematic data. This range is limited by numerical inaccuracies at very small radii and the fall off of the initial particle model's density at the edges. Many of the coefficients describe non-axisymmetric systems so they are set to zero in these models. In this case, the odd coefficients, all coefficients for which $m \neq 0$, and coefficients of higher order than $l=8$ are set to zero. The radial mass profile is assumed to have Poisson errors and the errors for the higher-order mass moments are determined through Monte Carlo simulations in which particles are drawn randomly to represent the density field of the target model. Fig. 5.22 shows the differential stellar mass distribution which is represented by

²The modeling of NMAGIC is a joint project undertaken with P. Das. The work and results from this work appear in both of our theses as well as a paper, of which we are two of the co-authors. My personal involvement in the process included preliminary spherical modeling, setting-up the axisymmetric models, and preparing the discrete tracer catalogs that constrain the outer parts.

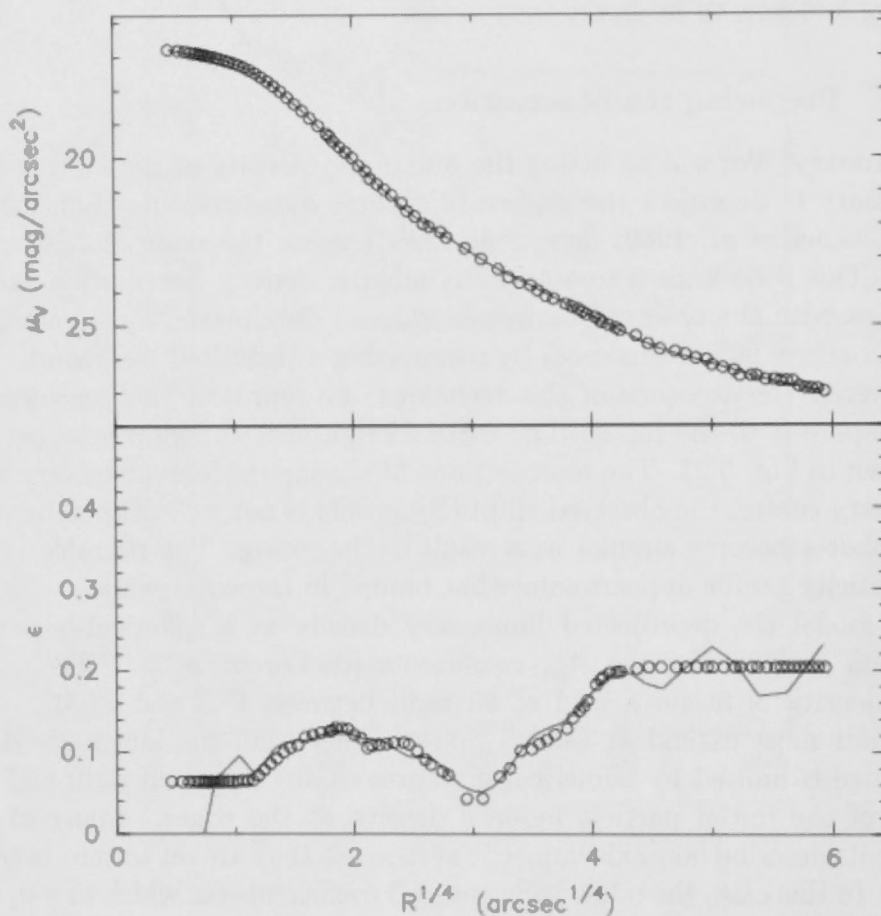


Figure 5.21 Projected light distribution for NGC 1399. **top:** The circles show the measured V-band surface photometry from Schombert (1986) and the line shows the reprojected surface brightness profile made from the axisymmetric deprojection ($i=90^\circ$). **bottom:** The black circles show the measured ellipticity profile from Caon et al. (1994). They are overplotted with the ellipticity profile of the reprojected light from the Magorrian-style deprojection.

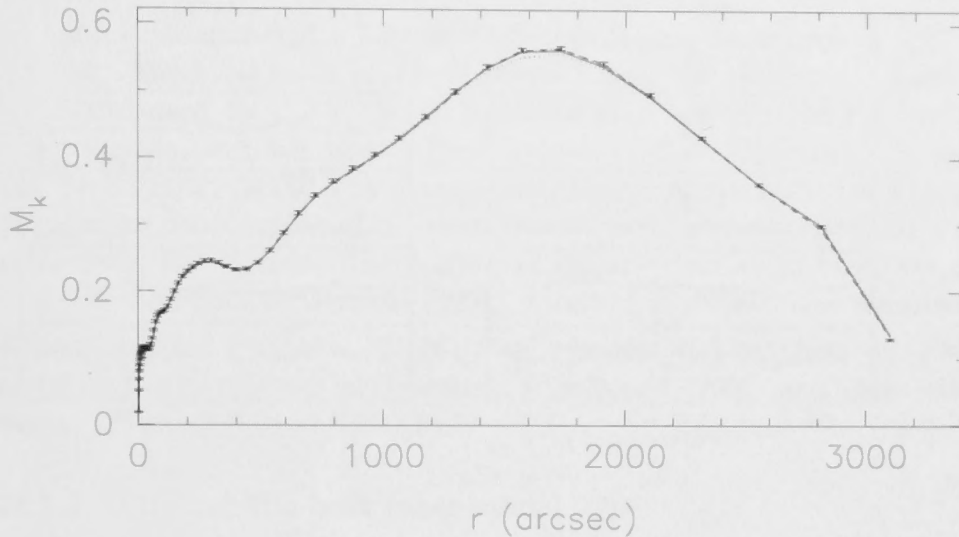


Figure 5.22 Differential mass distribution of the stars. The points show A_{00} coefficients calculated using the observed surface brightness data. They are compared to the differential mass distribution for four models: A (solid), B (dashed), C (dot-dashed) and D (dotted). In these models, we minimize χ^2 for all the data (A), the long-slit data only (B), major-axis long-slit data only (C) and discrete tracers only (D). In this plot, model D is distinguishable at the peak of the mass distribution and the other models appear the same at all radii.

the A_{00} coefficient.

Kinematics. Because we have assumed that the galaxy is axisymmetric, we can point symmetrize the kinematic data. For discrete tracers like PNe, the sample is doubled by adding an object at $(-x, -y, -v)$ for every object observed at (x, y, v) . The major-axis long slit kinematics are folded around the center of the galaxy. The reflected long-slit kinematics for both axes are shown in Fig. 5.23.

Our model will fit the light-weighted kinematics so we must calculate the amount of light in each spatial bin along the long slit. This is accomplished by integrating the surface brightness distribution over the dimensions of the cell using a Monte Carlo integration scheme. The slit is assumed to have a

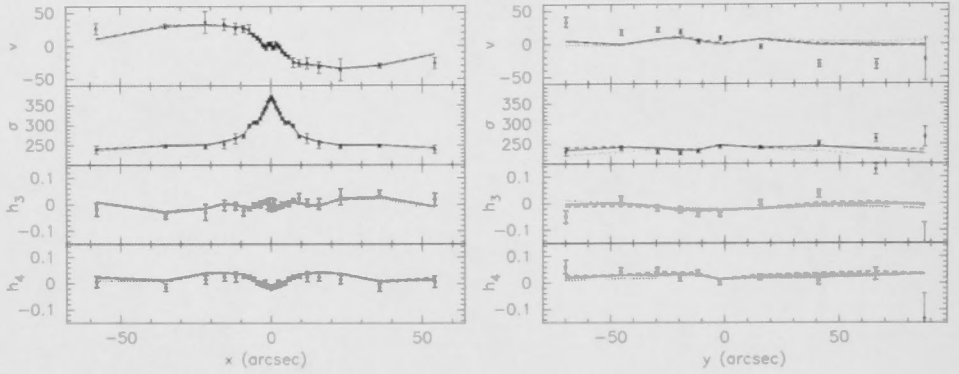


Figure 5.23 First four moments of the long-slit velocity distribution for NGC 1399. The points show observed and point-symmetrized values for the velocity, dispersion, skewness (h_3) and kurtosis (h_4) for the major (left panel) and minor (right panel) axes. The lines overplotted are our four models: A (solid), B (dashed), C (dot-dashed) and D (dotted).

width of $5''$ and the size of the bin along the slit varies inversely with the light.

The halo kinematics are constrained by PN and GC velocities. If the density profile is falling off with a power-law index of ~ 3 then the projected velocity dispersion traces the mass independently of anisotropy (Gerhard 1993). In this case, we only require robust measurements of the velocity and velocity dispersion to explore the dark matter halo instead of detailed information about the velocity distribution. This approach is much cheaper computationally than fitting individual velocities, but it relies on these simplifying assumptions. Like the long-slit kinematics, the discrete-tracer velocity bins are weighted by the light in each bin. The objects are point symmetrized before computing the velocity moments and binned in cones along the major and minor axes. The measurements made from this sample are shown in Fig.

5.24.

5.3.2.2 Initial conditions

Our initial model includes 750000 particles covering radii from $\sim 1''.5$ to $\sim 3100''$. The total mass profile is selected from the spherical dynamical models discussed in §5.3.1. It is the model that best fits the PN line-of-sight velocities, and it is toward the lower end of the 95% confidence range from Saglia et al. (2000). The density distribution of the particles matches the spherical deprojection of the circularly-averaged surface brightness measurements. The intrinsic distribution of stellar velocities is based on the circularity functions of Gerhard (1991), resulting in an isotropic anisotropy profile where $\beta \equiv 1 - \frac{\sigma_z^2}{\sigma_r^2} = 0$. The particles' positions and velocities are chosen according to the method in Debattista & Sellwood (2000) and their initial weights are equal ($w_i = 1/750000$).

5.3.2.3 Finding the best mass model

The total mass profile is comprised of a luminous component and a dark matter halo. For our model, we will find the total potential by exploring a range of mass models for both of these parts. The luminous component (Φ_*) traces the stellar luminosity profile. It is calculated during the modeling in the potential-solver step (see Fig. 4.2) which solves Poisson's Equation. This requires a measurement of the mass-to-light ratio, Γ , which is calculated using the technique implemented in NMAGIC and described in §3.6 of de Lorenzi et al. (2008). Γ_B has an initial value of 10 based on the work in Saglia et al. (2000).

The dark matter component of the total potential, Φ_{DM} , is parametrized in this case by a logarithmic profile (Binney & Tremaine 1987):

$$\Phi_{DM} = \frac{1}{2} V_0^2 \ln(r^2 + r_0^2), \quad (5.3)$$

where v_0 is the maximum circular velocity and r_0 is the scale radius. The dark matter component acts on the system as an external force.

To run the model, we begin with 2000 relaxation steps where the particles move in the potential, updating their positions and velocities, and their weights are not changed. The next 2000 steps temporally smooth the model—once again the particles advance without changing their weights. The main phase of the run involves allowing the particles to evolve in the potential according to the gravity acting on them and the weights of the particle are changed according to the force of change (FOC). This continues until

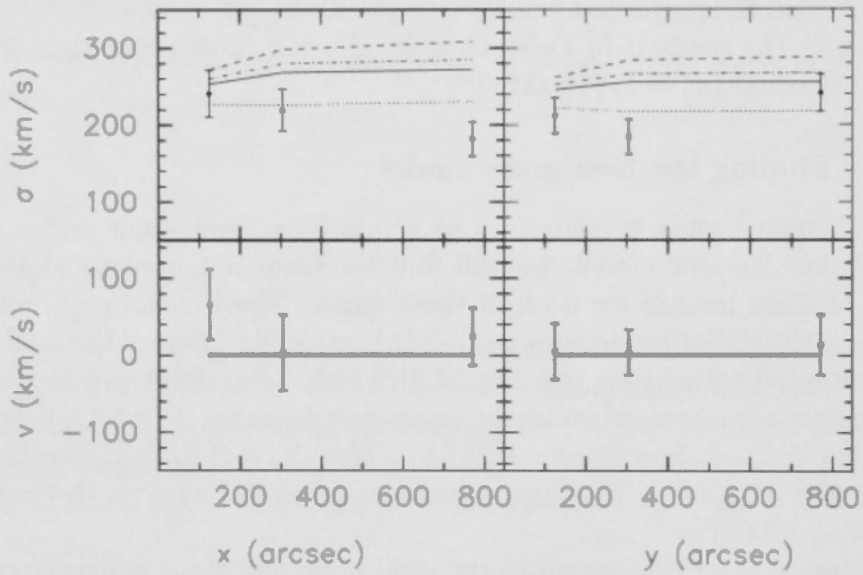


Figure 5.24 Combined PN and GC kinematic profiles. The objects have been point symmetrized, binned into cones and fitted robustly. The left panel shows the major axis and the right panel shows the minor axis. The lines overplotted are our four models: A (solid), B (dashed), C (dot-dashed) and D (dotted).

Table 5.7 NMAGIC models of NGC 1399. The columns give (1) the model, (2) the scale radius of the halo, (3) the maximum circular velocity of the halo, (4) the stellar B-band mass-to-light ratio, and the χ^2 goodness-of-fit for the (5) $A_{l,m}$ s, (6) long slit spectroscopy, (7) the major-axis only for the long-slit data, (8) the discrete tracer data, and (9) all the data. This table is reproduced directly from Das et al. (2011, in prep)

Model	r_0	v_0	Γ_B	$\chi^2_{A_{l,m}}$	χ^2_{LSS}	χ^2_{maj}	χ^2_{DT}	χ^2
	($''$)	(km s^{-1})	($M_\odot/L_\odot$)					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A	275	375	10.0	0.35	1.51	0.62	2.40	0.59
B	300	450	9.78	0.30	1.44	0.66	5.83	0.61
C	275	400	9.93	0.33	1.53	0.59	3.42	0.60
D	350	300	10.07	0.58	2.14	0.91	0.79	0.84

the fractional change in the total χ^2 falls below 1.5×10^{-3} , which we define as convergence. The final step is to allow free evolution where the particles advance in the potential for 30000 steps without changing their weights—this ensures that the final model is phase-mixed.

The modeling process is undertaken using a coarse grid of halos with core radii in the range $50'' < r_0 < 350''$ and circular velocities ranging from $300 < V_0 < 600 \text{ km s}^{-1}$. We use the bisection method to approach the best mass profile. We are able to resolve r_0 to $25''$ and V_0 to 25 km s^{-1} , which is the limit at which we can differentiate between the models. Fig. 5.25 shows the circular velocity curves for our four best-fit models.

We present four models in this work. Model A represents the best fit to all of the data. Model B is the best fit for the long-slit kinematics only and Model C minimizes χ^2 for only the major axis of the long-slit. Model D is the best fit for the discrete tracers alone. The parameters of the four models, including halo parameters, stellar mass-to-light ratios, and χ^2 values are summarized in Table 5.7. Figures 5.22, 5.23, 5.24 and 5.25 compare these models to observational constraints and other models.

Examining Fig. 5.25, models A, B and C are similar. They rise just short of 500 km s^{-1} at $\sim 10''$ and then dip down to below 400 km s^{-1} at $\sim 100''$ before rising gently to $\sim 450 \text{ km s}^{-1}$ in the halo. Model D resembles the others in the inner parts, but stays much flatter and lower in the outer parts. Model D's behavior indicates that the discrete tracers prefer a less massive halo than when we include all of the data. Additionally, this serves as an indicator that the long-slit kinematics dominate the discrete tracers in the overall χ^2 evaluation.

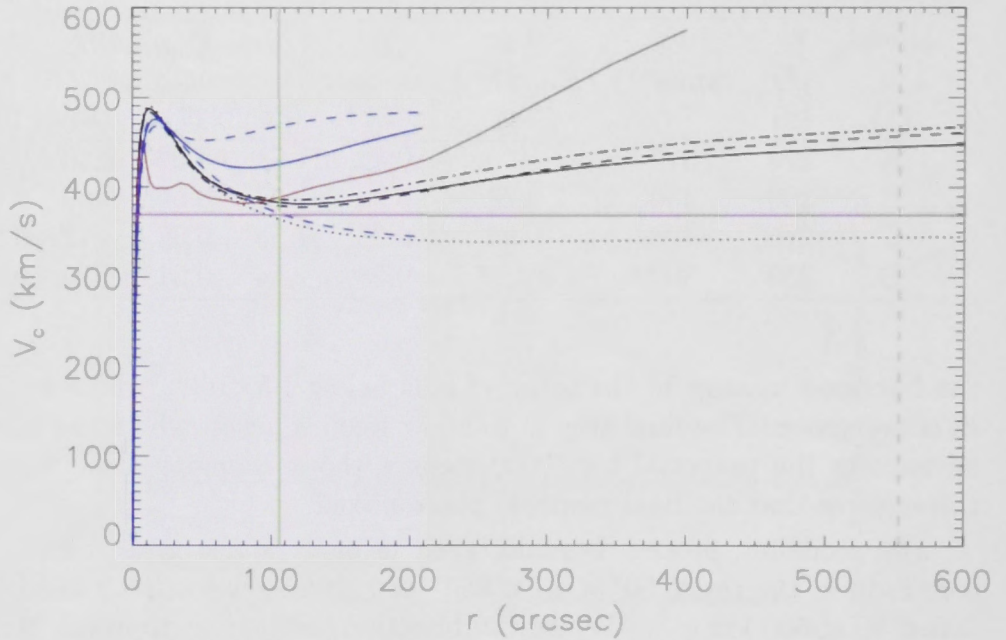


Figure 5.25 Circular velocity curves for NGC 1399. The black lines over-plotted are our four models: A (solid), B (dashed), C (dot-dashed) and D (dotted). Model A is the best fit to all of the data. Model B is the best fit for the long-slit kinematics only, and Model C is the best fit for the major-axis long-slit kinematics. Model D minimizes χ^2 for the discrete tracers. The red circular velocity curve is derived from X-ray observations (Das et al. 2010). The solid blue line is the the best fitting model selected from Kronawitter et al. (2000) shown with its 95% confidence range in dashed blue. The pink line represents the circular velocity predicted by the velocity dispersions of discrete tracers. The vertical green lines represent the radial limit of the constraints on the Kronawitter et al. (2000) models (solid) and the radial extent of the kinematic data presented here (dashed).

The fits to the $A_{l,m}$ s are very good as shown in Fig. 5.22. The χ^2 for Model D is slightly worse because the differential mass is systematically lower in the range 1300-1900".

Referring to Fig. 5.23, all four models fit the major-axis long-slit kinematics well with Model D doing slightly worse in the outer parts. The fits to the slit parallel to the minor axis are not as good. Because we imposed axisymmetry on the system, the models are symmetric about the major axis. The data show some rotation ($\sim 30 \text{ km s}^{-1}$) about the major axis and slight gradients in the other profiles. As shown in columns (6) and (7) in Table 5.7, the fits that include the minor axis long slits are worse than those using the major axis only.

The fits to velocity of the discrete tracers (planetary nebulae and globular clusters) are good and are barely distinguishable by eye. The modeling supports zero rotation in the outer parts. The velocity dispersion is not well fit by Models A, B and C which are systematically higher than the measured observables as shown in Fig. 5.24.

5.3.2.4 Interpretation

The goal of modeling NGC 1399 with NMAGIC is to learn about the total mass distribution, the stellar mass-to-light ratio and the orbital structure of the galaxy. Summarizing the conclusions from §5.3, we find a well defined circular velocity curve near the center with a maximum of $\sim 490 \text{ km s}^{-1}$. In the outerparts, the long-slit kinematics prefer a flat circular velocity of $\sim 450 \text{ km s}^{-1}$ whereas the discrete tracers favor a less massive halo with $V_0 = 340 \text{ km s}^{-1}$. Following the relation presented in Gerhard (1993), we expect $V_0 \approx 370 \text{ km s}^{-1}$, which is closer to the value predicted by the discrete tracers. If the discrete tracers had a bigger impact on the overall χ^2 , the range of models would have been in better agreement with this prediction.

Possible explanations for the discrepancy between the integrated-light and discrete tracers include incorrect assumptions about the shape of the stellar component or the dark-matter component. We can interpret the gradients in the parallel-to-minor-axis long slit to be an indication of triaxiality. The orbital structure is more flexible in a triaxial potential, and a mass distribution may exist that fits both the integrated light and the discrete tracers. Alternatively, the dark matter distribution could be more steeply concentrated towards the center like an NFW profile for example (Navarro et al. 1996). This would add mass to the central parts where the long-slit data dominates, but would allow for a lower-mass halo as preferred by the discrete tracers.

Comparing to independent estimates, Models A, B and C fall within the

95% confidence interval of the best fitting model from Saglia et al. (2000). As shown in Fig. 5.25, the circular velocity curve derived from X-rays (Das et al. 2010) is too low in the central parts and climbs steeply to become too high in the outer parts. Discussions of the deviation can be found in Churazov et al. (2010), Das et al. (2010) and Das et al. (2011, submitted to MNRAS).

Our models correspond to mass-to-light ratios in the range $9.8 < \Gamma_B < 10.1 M_\odot/L_\odot$. Because the logarithmic dark matter halo maximizes the stellar contribution at the centre, these mass-to-light ratios are upper limits. A steeper profile would give higher dark matter densities in the inner regions causing there to be less stellar mass and a lower stellar mass-to-light ratio. This range is in agreement with the value of 10 measured using similar assumptions by Saglia et al. (2000). It is also consistent with the estimate from Napolitano et al. (2005) $\Gamma_B = 10.4^{+3.3}_{-2.7} M_\odot/L_\odot$ calculated using single-burst stellar population models. As shown in Fig. 5.26, our models lead us to a dark matter mass content of 5-15% inside $1R_e(109'')$ and 55-75% at $5R_e$. These values agree with estimates in the literature (Gerhard et al. 2001; Cappellari et al. 2006; Thomas et al. 2007).

The four models display very similar orbital structures as is shown in Fig. 5.27. The orbits are somewhat radial along both axes with the major axis showing slightly more radial structure. The azimuthal and meridional velocity dispersions are almost equal until $r=100''$ on the major axis where the azimuthal orbits begin to dominate. All four models are in good agreement. It would be possible to improve our constraints on the orbital structure by fitting individual line-of-sight velocities for the discrete tracers using an integrated, robust-fitting technique inside NMAGIC.

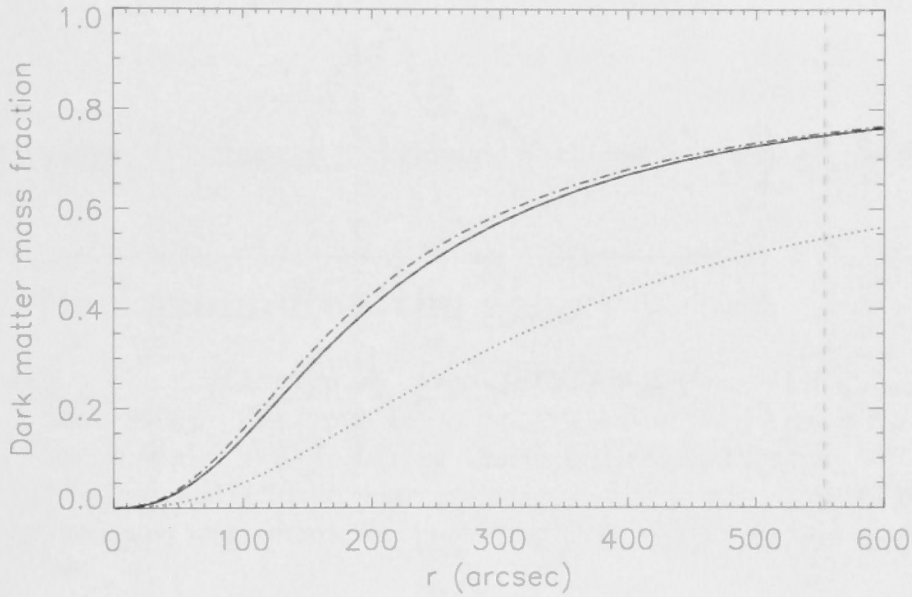


Figure 5.26 Dark matter mass fraction for NGC 1399. The black lines show the fraction of the total mass contributed by dark matter for each of our four models: A (solid), B (dashed), C (dot-dashed) and D (dotted). The green dashed line shows the radial limit of the kinematic observations that constrain this estimate. As discussed in the text, the discrete tracers (Model D) prefer a less massive halo than the other tracers. $1R_e$ is $109''$.

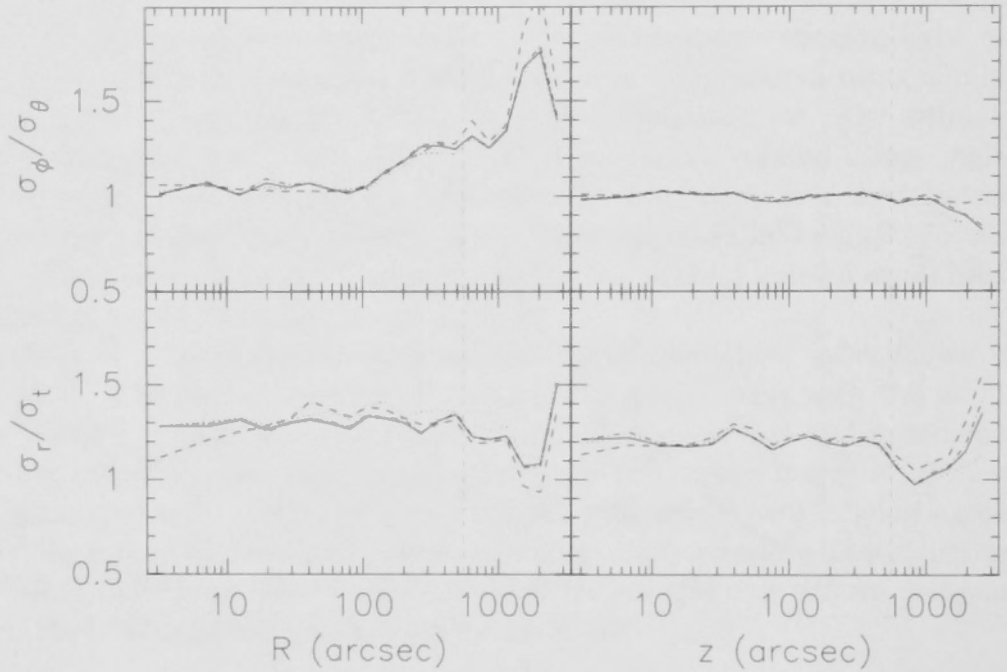


Figure 5.27 Orbital Structure of NGC 1399. The top panel shows the ratio of azimuthal to meridional velocity dispersion for the major (left panel) and minor (right panel) axes. The bottom panel displays the ratio of radial to tangential velocity dispersion following for the major and minor axes (left and right respectively). The black lines represent each of our four models: A (solid), B (dashed), C (dot-dashed) and D (dotted).

Chapter 6

NGC 3923

In this chapter we cover the background, results and analysis of the PN kinematics in NGC 3923.

6.1 Background on the galaxy

NGC 3923 is the brightest group galaxy (BGG) in a group of 8 galaxies (Brough et al. 2006). The group has a low fraction of early-type galaxies leading Brough et al. (2006) to suggest that it is dynamically young. NGC 3923 itself is remarkable for its extraordinary shell structure. Twenty-two nested and aligned shells mark the projected major axis of this E4 galaxy (Prieur 1988).

About 10% of elliptical galaxies have shell systems (Prieur 1990) and, for isolated ellipticals, 16.5% display shells Malin & Carter (1983). NGC 3923 is among the most famous shell ellipticals because its system is intact and well oriented for observation.

The interleaved nature of NGC 3923's shells caused Quinn (1984) to propose a formation model where the shells are formed by phase wrapping during a minor merger. Stars from the dynamically-cold, smaller galaxy travel along highly radial orbits and create over-densities near their apocenters. The implication is that a highly coherent system like NGC 3923 would be explained by the smaller galaxy encountering the larger on or near the major axis of a prolate or triaxial potential. The shell system could possibly provide welcome constraints on the orientation and intrinsic shape of NGC 3923. Shell formation has been modelled by several groups (Dupraz & Combes 1985, 1986; Hernquist & Quinn 1987; Prieur 1988), but the results do not spell out a one-size-fits-all formula for the interpretation of observations.

We assume that there is very little rotation along the major axis since the

Table 6.1 Observing log for NGC 3923*.

Field	P.A. Label	Exp. Time (s)	Seeing (FWHM)
NGC3923-1	W0	2×1800	$1.3''$
NGC3923-1	E180	2×1800	$1.4''$
NGC3923-2	W0	2×1800	$1.2''$
NGC3923-2	E180	2×1800	$1.4''$
NGC3923-3	W0	2×1800	$1.4''$
NGC3923-3	E180	2×1800	$1.2''$
NGC3923-4	W0	2×1800	$1.2''$
NGC3923-4	E180	1×1800	$1.6''$

* Each field is observed at P.A.= 0° and 180° , labeled W0 and E180 respectively.

shells are so intact. Additionally, the shell system extends into the region where we expect dark matter to dominate possibly allowing us to probe the clumpiness of the mass distribution. The systemic velocity of NGC 3923 is 1739 km s^{-1} according to Kaldare et al. (2003).

NGC 3923 is well studied. Particular interest has been paid to photometry with careful unsharp masking to reveal the shells (Malin & Carter 1983). Surface brightness profiles extend to $1000''$ (Jedrzejewski 1987; Prieur 1988). Buote & Canizares (1998) measured the hot X-ray gas and Carter et al. (1998) provides integrated light kinematics to $40''$. The globular cluster system was most recently studied by Norris et al. (2008) resulting in spectroscopy for 29 objects. Despite the obvious interest in the outer parts of this galaxy owing to the shells, there are not previously-published studies of the planetary nebula population in NGC 3923.

6.2 NGC 3923 PN velocity catalog

6.2.1 Observations

6.2.1.1 Planetary Nebulae

The planetary nebula kinematics of NGC 3923 were measured using counter-dispersed spectroscopy with FORS2 on the VLT (Appenzeller et al. 1998). The 4 fields covering the galaxy in Fig. 6.1 were observed on 13-15 April 2003. The observing conditions are summarized in Table 6.1.

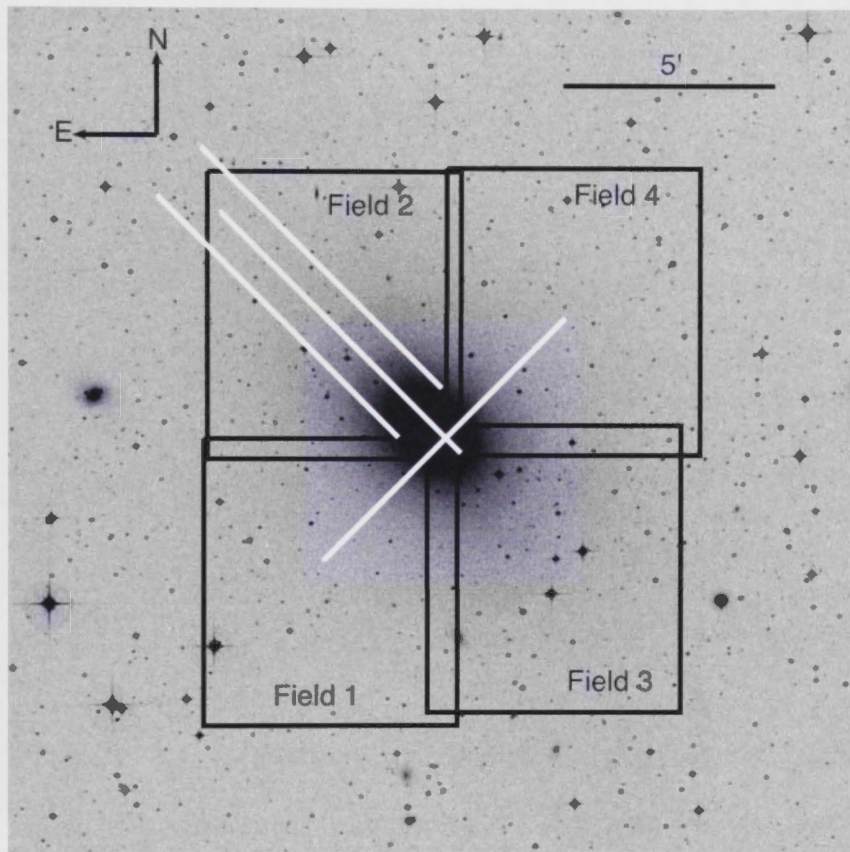


Figure 6.1 DSS image of NGC 3923 showing the approximate positions of the four fields observed. The practical observed area is somewhat smaller since the two counter-dispersed exposures of each field did not overlap completely. The white lines mark the long slits used for the integrated light measurements in §6.2.4. The three parallel slits lie on or parallel to the major axis (from bottom-left to top-right: slit 2, slit 1 and slit3). Slit 4 sits parallel to the minor axis (offset by $14''$).

The FORS field-of-view is $6'.8 \times 6'.8$ or 45.3kpc on each side at 22.9 Mpc for NGC 3923 (Tonry et al. 2001). The spatial scale is $0''.25$ /pixel.

We used the 1400V grating with a measured mean dispersion of $0.63 \text{ \AA/pix}^{-1}$. The arclines in the calibration frames have an average FWHM of $2.2 \text{ \AA}$ (133 km s^{-1}). An interference filter, FILT_503_5+86, was used to select emission at the wavelength of the redshifted [OIII] line. The filter prevents spectra of continuum sources from overwhelming the field, and it allows $> 50\%$ -transmission detection of PNe in the range of -720 to 2280 km s^{-1} .

These observations were done using counter-dispersed spectroscopy as described in §2.1.2. The field is imaged with a grism in the light path. This causes continuum sources such as stars to appear as streaks in the direction of dispersion. Emission-line objects such as planetary nebulae appear as dots. Another exposure is taken with the position angle (P.A.) rotated 180° . The distance between the emission-line objects detected in the P.A.=0 and P.A.=180 frames is a function of the object's velocity. Fig. 6.2 shows the four P.A.=0 fields from the NGC 3923 observations with streak-like stars and the PNe circled in white.

In all included counter-dispersed-spectroscopy figures, the direction of dispersion is along the horizontal axis (x -axis). Both the x - and y -axes contain spatial information due to the slitless technique. The grism causes an anamorphic distortion in the focal plane including contraction in the direction of dispersion. Detailed information on the reduction techniques used for this data is found in §2.1.2, 5.2.2, and McNeil et al. (2010).

6.2.1.2 Integrated-light spectroscopy

Long-slit spectra of the integrated stellar light for NGC 3923 were also observed with FORS2 on the VLT. The observations were done on 2-4 June 2008 in Service Mode. The program includes one minor-axis slit and three major-axis slits— one extending directly along the major axis piercing the shell system and two of which are offset to extend the radial reach of our measurements. See Fig. 6.1. Sky was taken from the faint ends of the slit so that the science and sky exposures were simultaneous, as recommended by Coccato et al. (2010).

The observations used the 1400V grism resulting in a measured dispersion of $0.64 \text{ \AA}$ per pixel over the range $4560\text{--}6000 \text{ \AA}$. The $2''$ slit is $448''$ long and placed at a position angle (P.A.) of 45° for the major axis and 135° for the minor axis. The MIT/LL Mosaic CCD was binned 2×2 for a pixel scale of $0.25''$ /pixel. The gain is $0.7 \text{ e}^-/\text{ADU}$ and the read noise is 2.9 e^- per pixel.

In addition to the major and minor axes, three template stars were observed. HR 6770, HR 5601 and HR 5690 represent spectral types G8III,

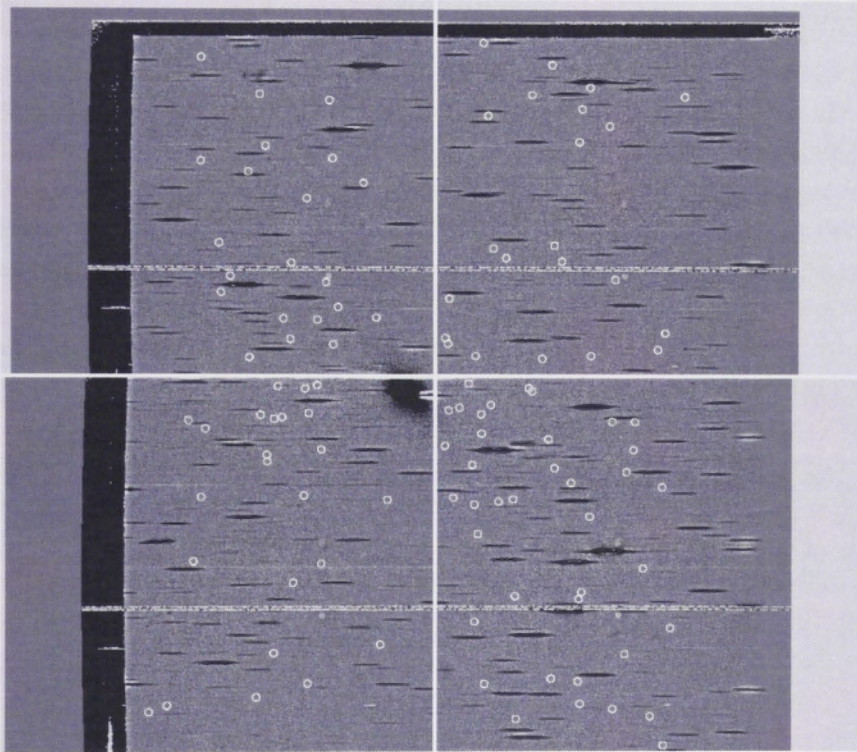


Figure 6.2 Mosaic of the counter-dispersed images of NGC 3923 overlaid with the 108 observed planetary nebulae. The core of the galaxy is near the center of the four fields. North is up. The streaks are foreground stars, and they indicate the direction of dispersion. The vertical stripe in the center without any PNe is due to non-overlapping counter-dispersed exposures.

K0.5III and K5III respectively. They are used to fit the line-of-sight velocity distribution (LOSVD) of the stellar light. The instrumental set-up for the template stars is identical to the long-slit spectroscopy of the galaxy, but the reduction is simpler because we are only extracting the spectrum of one point source, and sky is not significant in the templates' very short exposure times. The reduction technique for the long-slit spectra is described in §6.2.4.

6.2.2 Cataloging and isolating the planetary nebulae

The observations for NGC 3923 were reduced and registered using similar techniques to those used for NGC 1399 and NGC 1316 detailed in §2.1.2, §5.2.2, and McNeil et al. (2010). Using registered images, PNe were detected by blinking the two counter-dispersed exposures. A good detection has a pair of emission-line sources (one in each exposure) of approximately the same brightness and at the same y-position. The separation between the objects must be consistent with the transmission limits of the filter. To estimate and improve the completeness of the catalog, two independent attempts at the detections are undertaken a few days or weeks apart.

In contrast to the NGC 1399 and NGC 1316 reductions, NGC 3923 employed the cosmic ray removal software, L.A.Cosmic (van Dokkum 2001). This step proved necessary because each pointing was observed with only two exposures. The observations for NGC 1316 and NGC 3923 were done using FORS2 instead of FORS1. This enabled a more effective calibration set-up with a drilled mask instead of the series of calibration slitlets described in §5.2.2. The distortion correction and registration is the same as the one described in that section, but the calibration positions appear less extended in the vertical direction, which makes them easier to measure.

The astrometry was performed following the steps described in §5.2.5. The position of each PNe is taken to be the mean of the detections in the two counter-dispersed exposures. The astrometric solution is based on the measured positions of the stars and the coordinates of the corresponding objects in the USNO-B catalog (Monet et al. 2003). The uncertainty in these positions includes the difficulty of measuring bandpass-shifted continuum sources, but, based checks in §5.2.5, it is dominated by the $0''.3$ uncertainties on the USNO-B coordinates.

6.2.3 Velocity calibration

Compared to the FORS1 observations which were calibrated with a grid of slitlets, the FORS2 observations use a drilled calibration mask that is easier to use. Therefore, we are confident in the NGC 3923 PN absolute and

relative velocities. In the case of this galaxy, we were not able to verify the field-to-field calibration because there were no duplicate PNe in the (very small) regions of overlap. This is partly because the two counter-dispersed exposures of each field do not cover the same area so the coverage is not complete as illustrated in Fig. 6.2. The mean of the sample ($1716 \pm 30 \text{ km s}^{-1}$) is consistent with systemic velocity of the galaxy (Kaldare et al. 2003).

Normally, we would use the duplicate PNe to estimate the instrumental error for the sample. Since that is not possible for this galaxy, we adopt the instrumental error of NGC 1316 since those observations use the same instrument, set-up and calibration procedure. We define the observational error to be 30 km s^{-1} , which is calculated in §7.2.2.1.

6.2.3.1 Contamination from other sources

Compared to NGC 1399 and NGC 1316, NGC 3923 is a relatively isolated galaxy found near the center of a group rather than a cluster. As such, we consider there to be negligible contamination from PNe belonging to other galaxies. Many of the emission-line objects in our observations are, upon close inspection, associated with continuum, are spatially extended or display faint double emission. They are not PNe (see §5.2.3.3) and we can remove these objects from our sample. There are other possibilities for contamination from emission-line objects that cannot be distinguished from PNe. They are likely to be Lyman- α galaxies at $z=3.1$.

These background galaxies have a velocity distribution that matched the transmission of the filter which allows us to estimate the level of contamination. They are extremely difficult to remove because their spatial distribution is flat over our observations. Ciardullo et al. (2002) estimated the contamination in $\lambda 5007$ surveys and Gronwall et al. (2007) provide estimates for background levels of these galaxies, but those methods require photometry of the candidates. We minimize contamination by selecting the most bright and unambiguous emission-line sources for the catalog. Referring to the velocity histogram of NGC 3923 displayed in Fig. 6.3, we consider the presence of background galaxies in the PN catalog to be limited and, using robust methods, we can move forward with our analysis.

6.2.3.2 PN catalog

The final sample of 108 PNe in NGC 3923 is shown in Fig. 6.3. There is an excerpt of the catalog of PNe and their velocities presented in Table 6.2, and the full table will be made available when this work is published.

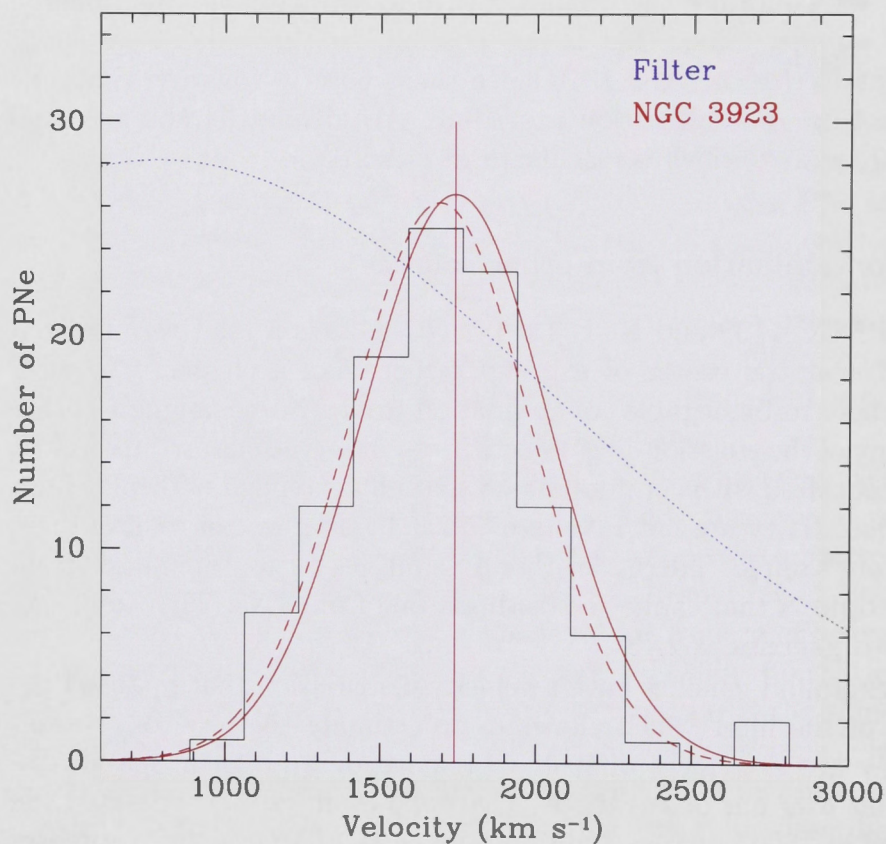


Figure 6.3 Velocity histogram of the PNe in NGC 3923. The red solid curve represents a Gaussian distribution with a mean velocity of 1739 km s^{-1} (Kaldare et al. 2003) and a dispersion of 300 km s^{-1} . The blue dotted curve representing the filter is shown to give an indication of transmission as a function of wavelength. The red, dashed curve is the product of the red and blue curves, which shows the effect that the filter has on the sample.

Table 6.2 Catalog of PNe in NGC 3923

ID	RA J2000	Dec J2000	wavelength Å	v_{helio} km s ⁻¹
NGC3923 1	177.66710	-28.71921	5031.3	1444
NGC3923 2	177.67018	-28.87554	5035.9	1722
NGC3923 3	177.67189	-28.90988	5029.6	1345
NGC3923 4	177.67289	-28.83417	5036.1	1736
NGC3923 5	177.67442	-28.78843	5036.9	1782
NGC3923 6	177.67560	-28.79318	5026.0	1128
NGC3923 7	177.67594	-28.90134	5027.2	1199
NGC3923 8	177.67887	-28.85807	5033.7	1587
NGC3923 9	177.68236	-28.82324	5036.3	1747
NGC3923 10	177.68374	-28.81510	5051.8	2674
⋮	⋮	⋮	⋮	⋮
NGC3923 106	177.83123	-28.81453	5034.9	1658
NGC3923 107	177.83856	-28.89811	5033.2	1560
NGC3923 108	177.84486	-28.89986	5036.0	1729

NOTES - Details on the astrometry are in §6.2.2. Velocities are corrected to heliocentric. Errors on the velocities are 30 km s⁻¹ as calculated in §7.2.2.1. The full catalog will be included in a future publication.

6.2.4 Extracting line-of-sight velocities from integrated light

The NGC 3923 long-slit spectra are bias-subtracted, flat-fielded, rectified and wavelength-mapped using the standard FORS Pipeline (Izzo et al. 2010). Three equal exposures were summed using a maximum value rejection for cosmic ray removal. See Fig. 6.1 for the placement of the long slits with respect to the galaxy. The sky is taken to be the sigma-clipped median of 100 lines at the faint edge of the slit. For the major-axis slits, this is 100 lines from the northern end. It is 50 lines from each end of the minor-axis slit.

The line-of-sight velocity distribution is fitted using the shape of the absorption-line profiles in our spectra. We used the Gauss-Hermite pixel fitting software developed by R.P. van der Marel (1994). Comparison spectra are created by convolving a template star with velocity profiles parameterized as a Gauss-Hermite series. The best fit is found by comparing the observed galaxy spectrum to the convolved spectra and minimizing χ^2 in pixel space. The step-by-step instructions for implementing this code are documented in §3.1.2. Further details of the software are discussed in van der Marel (1994).

To obtain our fits, the 2D spectra were progressively binned in the spatial dimension to achieve the requested signal-to-noise (75-125 per pixel). We fit the first four moments of the velocity distribution: v , σ , h_3 and h_4 . See Chapter 3 and Bender et al. (1994) for an explanation of h_3 and h_4 values. Our results are described in §6.2.5.2.

6.2.5 Kinematics of NGC 3923

6.2.5.1 Phase-space distribution of PNe

The 108 planetary nebulae in NGC 3923 are detected across 4 fields. The positions of the four fields and the 108 PNe are shown in Fig. 6.1 and 6.2. The spatial distribution of the catalog overlaid with a schematic diagram of the shell system is shown in Fig. 6.4. The phase space diagram shown in Fig. 6.5 is centered near $v_{sys} = 1739 \text{ km s}^{-1}$ (Kaldare et al. 2003).

We fit the rotation of the PNe assuming that the galaxy is spherically symmetric, the amplitude of rotation is only a function of radius and that the axis of rotation is in the plane of the sky (Côté et al. 2001; Woodley et al. 2010). The velocity as a function of position angle, Θ , is parametrized as

$$v_p[\Theta] = V_{sys} + A \cos(\Theta - \Theta_0),$$

where V_{sys} is the systemic velocity, A is the amplitude of rotation, and Θ_0 is the P.A. of the kinematic major axis.

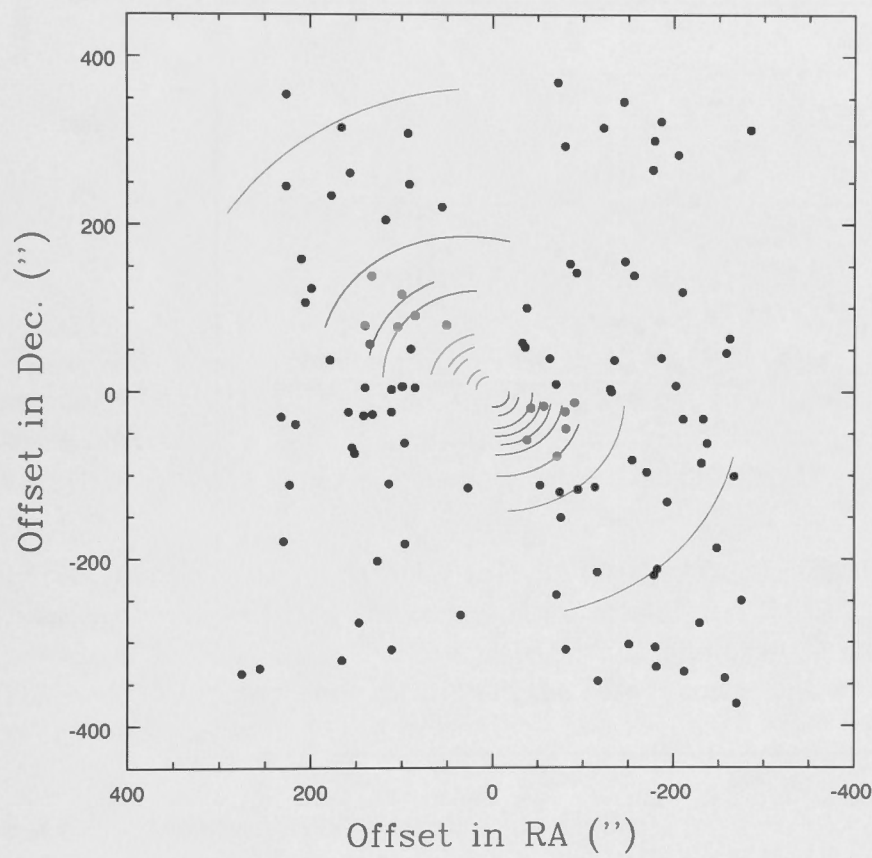


Figure 6.4 Spatial distribution of the 108 objects in the NGC 3923 observations. North is up and East is left. The arc segments illustrate the location of the shells summarized in Table 2 of Prieur (1988).

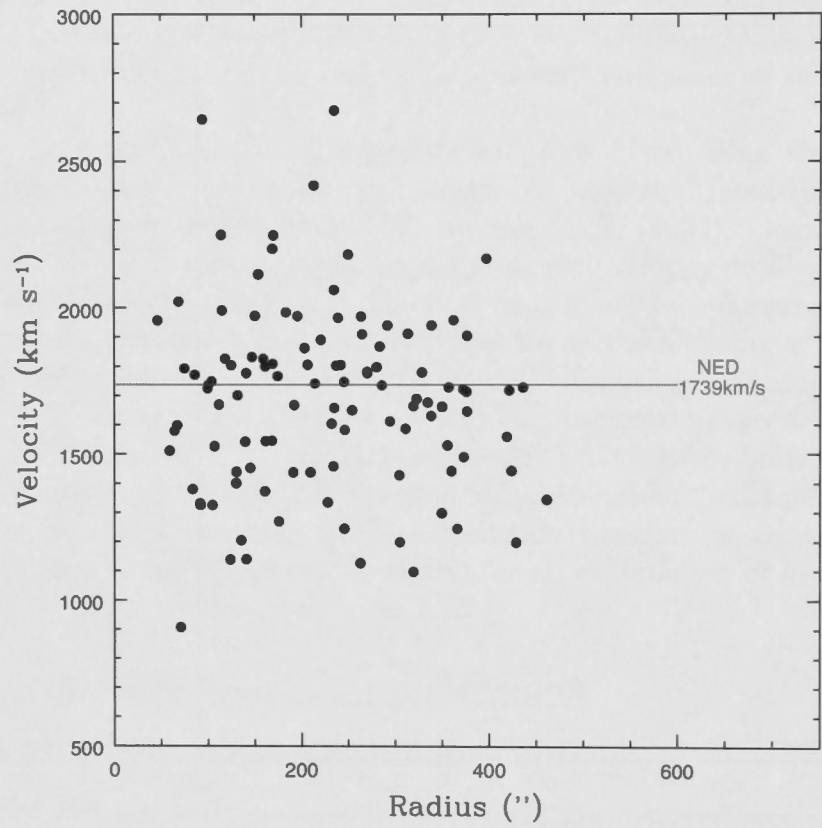


Figure 6.5 Comparison of line-of-sight velocity to projected radius. Although it is difficult to tell with a sample this size, we do not see strong structure in this sample. The solid line represents the systemic velocity of the galaxy published by Kaldare et al. (2003)

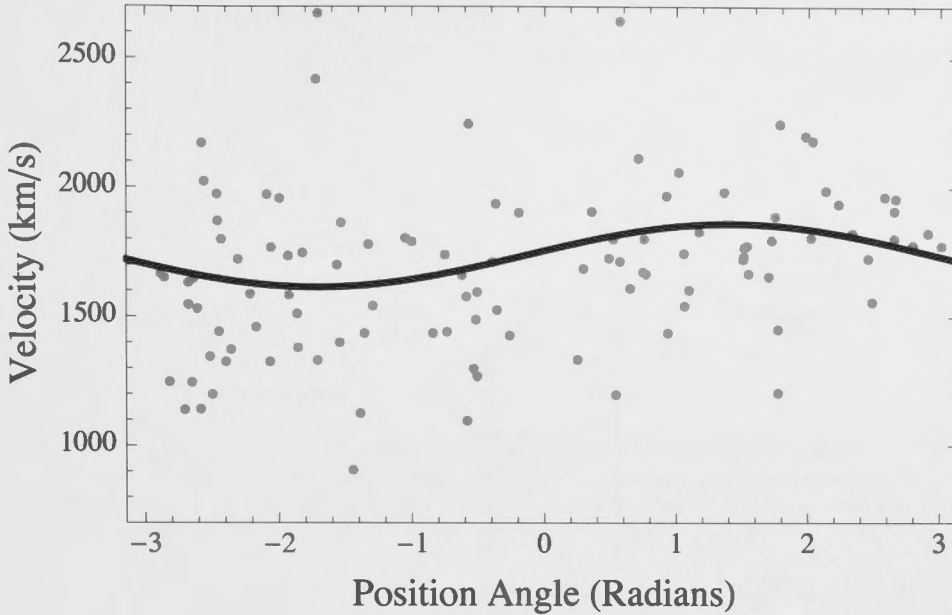


Figure 6.6 Fitted rotation of the PNe in NGC 3923. Gray dots mark the velocities of the 108 PNe in NGC 3923 as a function of position angle. The black curve shows the fitted rotation. The amplitude of rotation is 125 ± 45 km s^{-1} and the P.A. of the kinematic major axis is $81 \pm 23^\circ$.

We set the systemic velocity to 1739 km s^{-1} Kaldare et al. (2003). The resulting rotation has a kinematic major axis at $\text{P.A.} = 81 \pm 23^\circ$ and an amplitude of $125 \pm 45 \text{ km s}^{-1}$. See Fig. 6.6. The photometric major axis is at $\text{P.A.} = 45^\circ$. The amplitude rotation of the PNe is consistent with the rotation of the light shown in Fig. 6.8.

6.2.5.2 Long-slit velocity distributions

The first four moments of NGC 3923's central line-of-sight velocity distribution are plotted in Fig. 6.7 and tabulated in Tables 6.4 and 6.3. The results indicate negligible rotation along either axis, a falling dispersion profile over this radial range and constant anisotropy. These values compare extremely well with the measurements in Carter et al. (1998). The exceptionally high dispersion value at $\sim 25''$ is probably due to some contamination from a background source—the light profile for this spatial bin shows an unusual feature in an otherwise smooth surface-brightness distribution.

As we extend to larger radii along the major axis, the velocity distribution changes as illustrated in Fig. 6.8. Table 6.4 summarizes the results. These data extend only to the north of the galaxy, and we observe a climbing

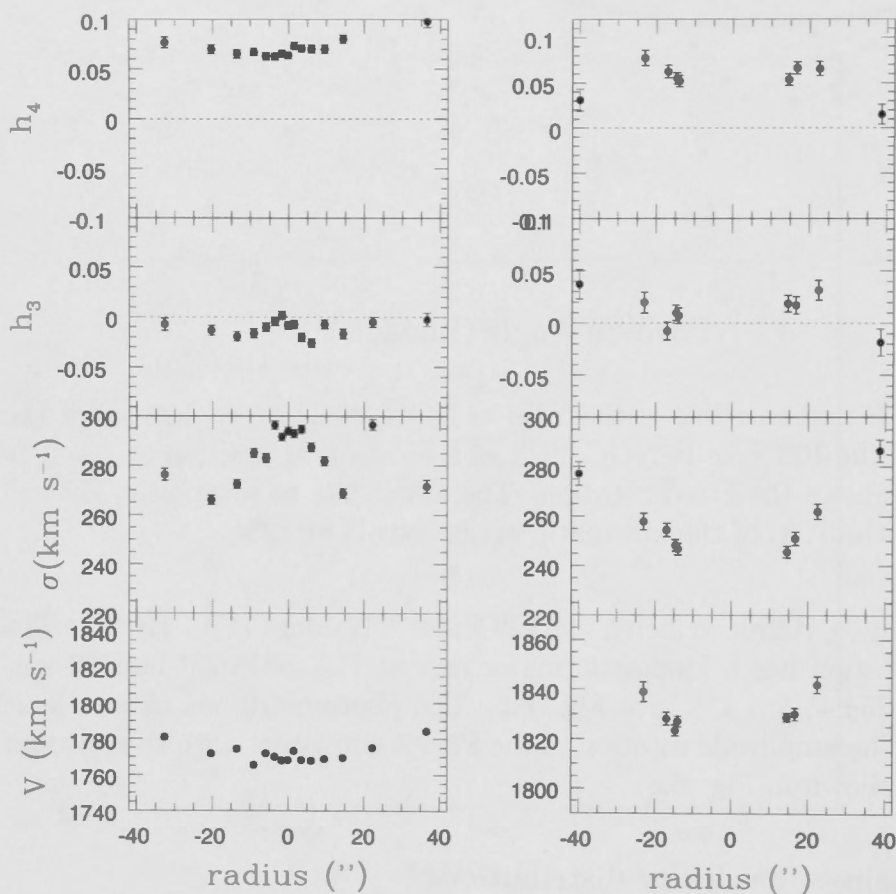


Figure 6.7 Major- (left) and minor- (right) axis velocity profiles for NGC 3923. The velocity and h_3 profiles both indicate negligible rotation within $40''$. As expected the velocity dispersion is strongly peaked at the center and falls as you go outwards. The flat h_4 profile implies basically constant anisotropy as a function of radius.

Table 6.3 Minor-axis integrated light kinematics of NGC 3923

Radius ($''$)	v	Δv	σ	$\Delta \sigma$	h_3	Δh_3	h_4	Δh_4
-40.0	1882.1	3.1	277.2	4.8	0.0370	0.0141	0.0312	0.0119
-23.0	1839.0	4.1	257.9	3.4	0.0197	0.0102	0.0775	0.0084
-16.9	1828.1	2.6	254.5	2.7	-0.0076	0.0085	0.0624	0.0070
-14.6	1823.5	2.2	248.3	2.3	0.0098	0.0076	0.0550	0.0062
-14.0	1827.0	2.1	246.8	2.3	0.0072	0.0075	0.0520	0.0061
14.5	1828.8	1.7	245.6	2.4	0.0187	0.0078	0.0535	0.0063
16.7	1830.1	2.5	251.0	2.6	0.0173	0.0083	0.0663	0.0068
22.5	1842.1	3.4	261.9	3.1	0.0316	0.0096	0.0654	0.0080
38.6	1873.5	1.9	286.4	4.5	-0.0184	0.0129	0.0152	0.0110

NOTES - Velocities and velocity dispersions are measured in km s^{-1} . Velocities are adjusted for the velocity of the template star and corrected to heliocentric. The radii of the bins has been offset to account for the slit's position $14''$ from the center.

velocity profile as if the outer parts are rotating with an amplitude of about 125 km s^{-1} . This agrees well with the fitted rotation of the PNe. The dispersion profile seems to rise again beyond $50''$. The dropping h_4 profile implies that the stellar orbits in the outer parts are more tangential.

6.2.5.3 Rotation in the outer parts

The measured rotation of the PNe and integrated light has some implications regarding shell formation. Hernquist & Quinn (1989) argued that a highly-aligned system like NGC 3923 must form by a chance radial encounter aligned with a major axis. The measured rotation makes more relaxed scenarios more appealing. One possibility for the central galaxy is an edge-on, rotating axisymmetric system with the shell material following a tight $E\text{-}L_z$ relation, although not necessarily one with $L_z=0$. This case would provide a nice constraint on the intrinsic shape of the galaxy. Another possibility is a prolate or triaxial galaxy slowly tumbling along the line of sight with the shortest axis in the plane of the sky. The existence of nested and aligned shells implies that the potential must be time-invariant over the shell-formation time, so the tumbling timescale must be long ($>\sim 2\text{Gyr}$) compared to the oscillations of the stars in the shells. NGC 3923 shows no sign of isophotal twist at large radii, which argues against a triaxial distribution.

The observations of the outer parts provide new information on the intrinsic shape of NGC 3923 and the merger geometry. The implication is that even the most ordered and aligned shell system is not subject to highly restrictive formation scenarios. The oblate rotator scenario may only require the encounter to be in the equatorial plane instead of a radial merger along a major axis. The extension of kinematic constraints opens up possibilities for learning how shells form around early-type galaxies. Observations from the negative major axis would be helpful in confirming this result.

6.2.5.4 Velocity dispersion measurements

The line-of-sight velocity dispersion profile is a useful tool to illustrate the mass distribution and dynamics of elliptical galaxies. For our measurements, we use a robust technique for measuring the dispersion of discrete tracers that is described in §5.2.7.2. Because the calculation is only based on objects lying within 2σ of the mean, outliers do not have a strong effect. This method is resilient against any lingering contamination from background galaxies.

The dispersion profile of NGC 3923 is shown in Fig. 6.9. The combination of new and existing (Carter et al. 1998) integrated-light measurements fall to $\sim 250 \text{ km s}^{-1}$ only to rise again. The anomalously high measurement at

Table 6.4 Major-axis integrated light kinematics of NGC 3923

Radius (")	v	Δv	σ	$\Delta\sigma$	h_3	Δh_3	h_4	Δh_4
Slit 1:								
-32.7	1837.8	1.6	269.2	2.3	-0.0059	0.0068	0.0582	0.0057
-20.4	1828.3	1.5	257.1	1.8	-0.0085	0.0057	0.0572	0.0047
-13.6	1830.4	1.4	261.4	1.7	-0.0022	0.0051	0.0508	0.0043
-9.1	1821.7	1.2	272.5	1.6	0.0005	0.0048	0.0523	0.0040
-5.9	1827.4	1.9	271.6	1.5	0.0072	0.0045	0.0472	0.0038
-3.6	1827.6	1.2	283.3	1.5	0.0198	0.0043	0.0452	0.0037
-1.7	1825.3	0.9	279.3	1.5	0.0228	0.0041	0.0463	0.0035
-0.1	1825.8	1.1	280.5	1.5	0.0152	0.0042	0.0448	0.0036
1.5	1830.7	0.8	279.4	1.5	0.0124	0.0042	0.0519	0.0036
3.5	1826.3	1.2	282.4	1.5	0.0029	0.0043	0.0498	0.0037
6.0	1825.4	1.0	274.8	1.6	-0.0057	0.0046	0.0499	0.0039
9.5	1826.1	1.1	270.3	1.7	0.0139	0.0049	0.0519	0.0042
14.4	1826.3	1.6	257.9	1.7	-0.0059	0.0054	0.0623	0.0044
22.2	1835.9	1.4	288.1	2.1	0.0197	0.0054	0.1051	0.0046
36.5	1843.4	2.5	261.7	2.4	0.0033	0.0074	0.0749	0.0061
65.0	1873.3	1.2	262.6	3.7	0.0102	0.0109	0.0895	0.0091
Slit 2:								
76.7	1898.5	9.6	297.0	7.8	-0.0272	0.0199	-0.0365	0.0177
84.6	1896.1	7.5	299.9	8.4	-0.0204	0.0211	-0.0141	0.0188
93.3	1932.6	4.6	291.7	8.6	-0.0839	0.0234	-0.0803	0.0208
102.9	1949.8	5.7	275.3	8.9	-0.0263	0.0260	-0.1159	0.0229
113.5	1979.5	8.3	274.4	9.5	-0.1215	0.0296	-0.1580	0.0259
Slit 3:								
74.4	1843.2	6.5	300.2	7.3	0.0807	0.0178	0.0114	0.0159
81.9	1832.1	3.7	290.3	7.9	0.0912	0.0192	0.0525	0.0170
90.2	1868.8	5.2	314.1	8.8	0.0069	0.0205	0.0053	0.0185
99.4	1907.1	4.3	328.1	9.1	-0.0155	0.0216	-0.0907	0.0197
109.8	1958.9	2.6	316.7	10.2	-0.0447	0.0255	-0.1021	0.0230
121.3	2006.9	3.6	300.1	10.9	-0.0892	0.0284	-0.1937	0.0254

NOTES - Velocities and velocity dispersions are measured in km s^{-1} . Velocities are adjusted for the velocity of the template star and corrected to heliocentric. The radii of the bins in slits 2 and 3 have been shifted to account for the offset of the slits' positions.

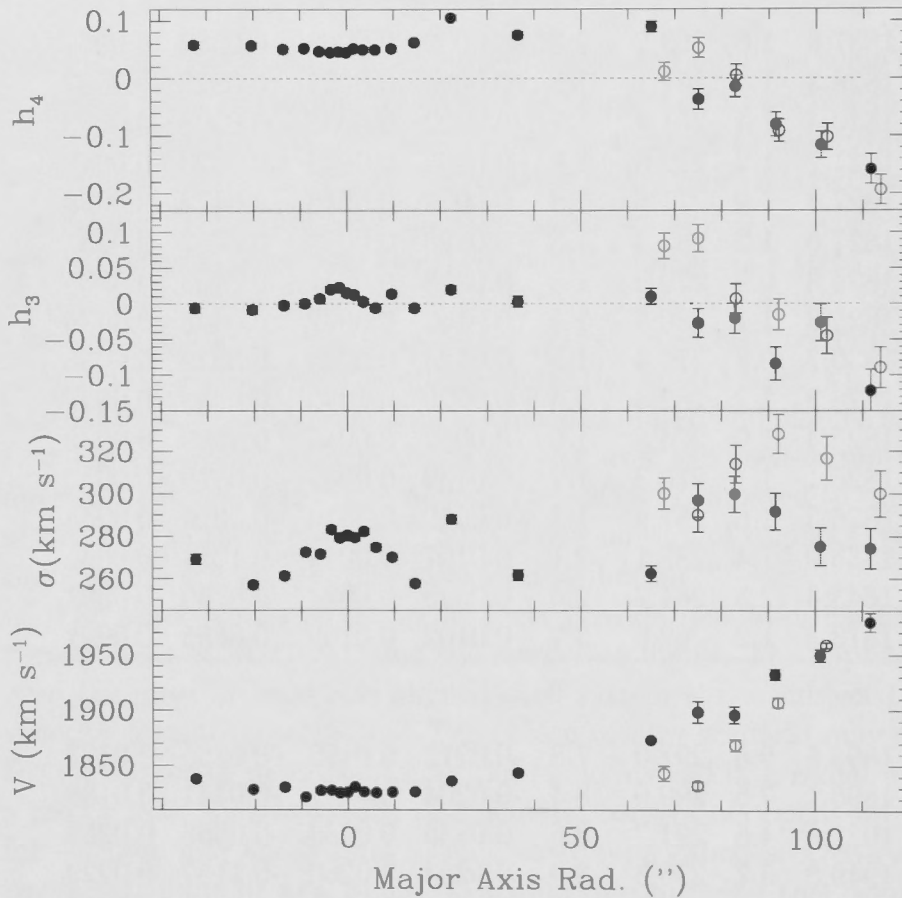


Figure 6.8 Composite of the three major-axis spectra of NGC 3923. Measurements from the two offset slits provide constraint on the velocity distribution outside 50". The black points inside 50" are derived from Slit 1. In the outer parts, solid points come from Slit 2 and hollow points from Slit 3. As we approach the halo, the behaviour changes. We see indications of climbing rotation, more tangential orbits and a climbing dispersion profile.

$\sim 25''$ is probably related to an unusual bump in the light profile in this spatial bin— it could be a background galaxy or star that contaminated the light in the slit and artificially raised the dispersion. We do not consider this point in our analysis of the galaxy's dispersion profile. Moving towards the outer parts, weighted averages for slits 2 and 3 agree that the dispersion profile is increasing, although the finer details plotted in Fig. 6.10 indicate slightly different shapes in this region.

At the edges of the observations, the PNe constrain the mass contribution of the DM halo. The 108 PNe are binned together to give one measurement. Especially seen on the linear scale of Fig. 6.10, the PNe imply a flat dispersion profile in the halo.

6.3 Dynamical Models

To better understand the meaning of the kinematics of the PN samples in NGC 3923, we construct a simple dynamical model of the galaxy. We follow the procedure for constructing Jeans models set out in §4.1. We begin with the Jeans equation (Binney & Tremaine 1987), assuming spherical symmetry:

$$\frac{1}{\rho} \frac{d(\rho \sigma_r^2(r))}{dr} + 2 \frac{\beta_0 \sigma_r^2(r)}{r} = - \frac{d\Phi}{dr}, \quad (6.1)$$

where ρ is the spatial density, σ_r is the velocity dispersion, β_0 is the anisotropy of the velocity distribution ($\beta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$) and Φ is the total potential.

The terms in Eqn. 6.1 can be related to observationally accessible quantities. We solve for the velocity dispersion and correct for the projection onto the plane of the sky. We fit the projected velocity dispersion of the model to the observed velocity dispersions of the stars and PNe. The projected velocity dispersion of the model is given as

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta_0 \frac{R^2}{r^2} \right) \frac{j(r) \sigma_r^2(r) r}{\sqrt{r^2 - R^2}} dr, \quad (6.2)$$

where $I(R)$ is the observed surface brightness profile and $j(r)$ is the light density which is calculated from the mass density, ρ , times a constant mass-to-light ratio, Γ .

The true velocity dispersion of the model, σ_r , depends on the total mass of the system. In some cases, it is possible to use an independent estimate. For NGC 3923 we have assumed that the total mass is comprised of a luminous component that traces the light with some constant mass-to-light ratio and a dark matter component parameterized as a pseudo-isothermal distribution

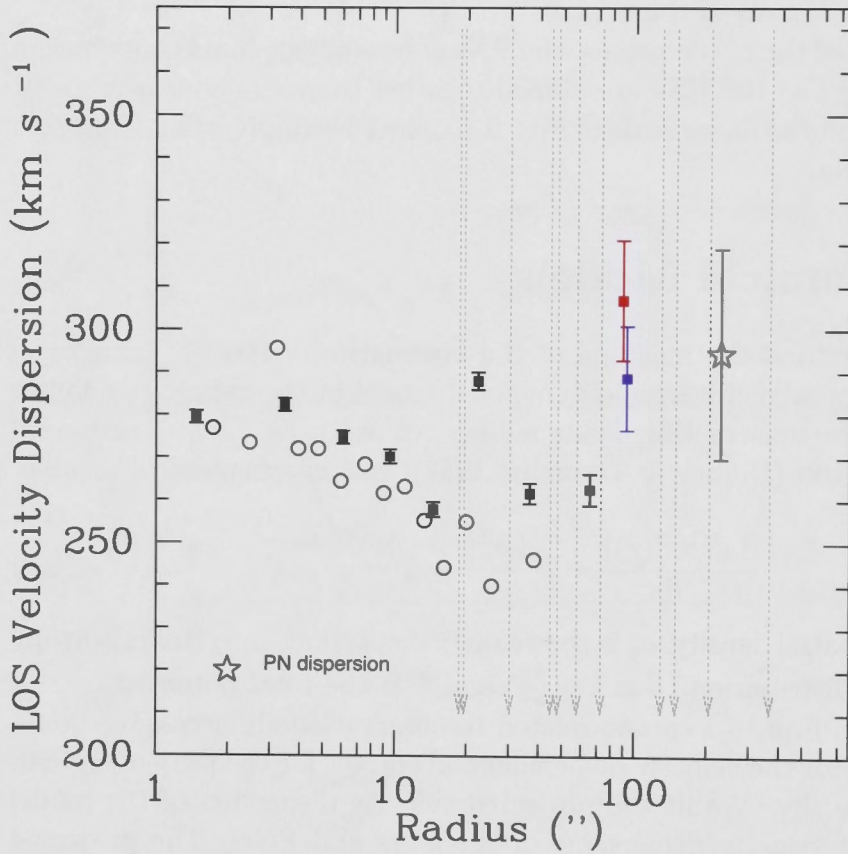


Figure 6.9 Dispersion profile of NGC 3923. The hollow circles represent the major-axis dispersion measurements from Carter et al. (1998). The solid black, blue and red squares are the major axis measurements from Slits 1, 2 and 3 respectively as discussed in §6.2.5.2. The PN dispersion measurement, shown as a hollow star, is calculated using the robust technique, and the instrumental error has been removed. The dotted arrows represent the radial positions of the shells from Prieur (1988).

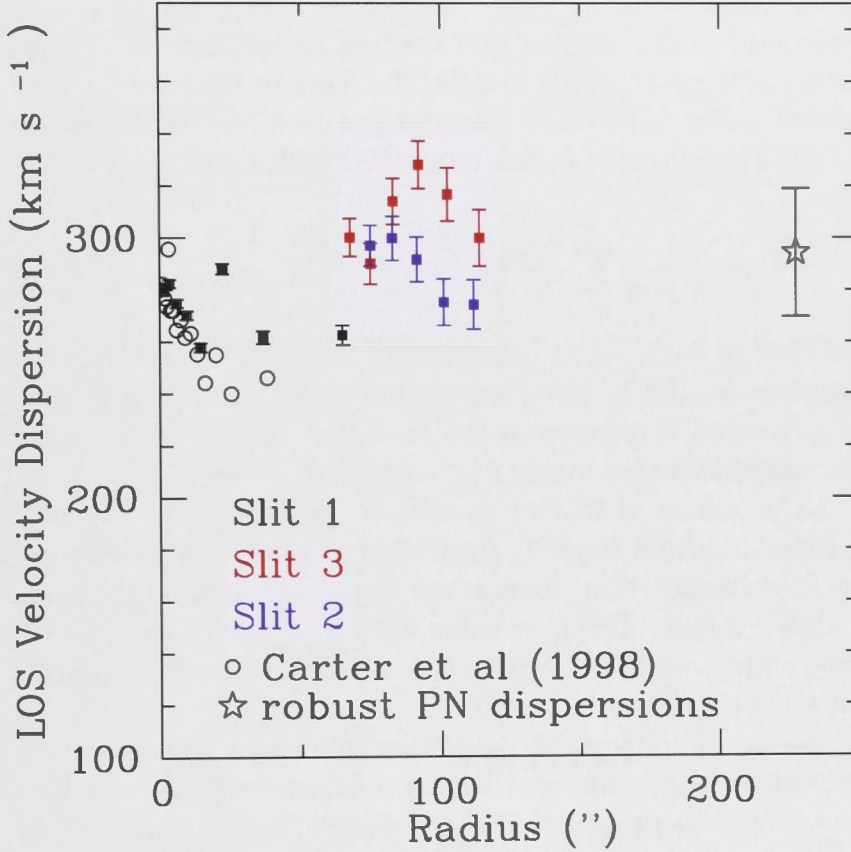


Figure 6.10 Linear dispersion profile of NGC 3923. The linear scale is chosen to show the detail of what is happening at the transition from integrated light to PN data. The hollow circles represent the major-axis dispersion measurements from Carter et al. (1998). The black, blue and red squares are the major axis measurements from Slits 1, 2 and 3 respectively as discussed in §6.2.5.2. The PN dispersion measurement, shown as a hollow star, is calculated using the robust technique, and the instrumental error has been removed. Despite being placed symmetrically with respect to the major axis, slit 2 shows a faster falling profile than slit 3. These measurements agree that the dispersion profile must be reasonably flat in the outer parts.

such that

$$\rho_{\text{DM}}(r) = \frac{\sigma_{\text{DM}}}{2\pi G(a^2 + r^2)}, \quad (6.3)$$

where σ_{DM} is a velocity dispersion representing the total mass of the DM halo and a is a core radius.

We explored a grid of models varying over the four parameters β_0 , Γ , σ_{DM} , and a . We resolved the anisotropy (β) to 0.25, the mass-to-light ratio (Γ) to $0.25M_{\odot}/L_{\odot}$, the core radius (a) to 0.25 kpc and the dark matter dispersion (σ_{DM}) to 5km s^{-1} . The goodness-of-fit was quantified with a reduced- χ^2 -style merit function,

$$\tilde{\chi}^2 = \frac{1}{N - n} \sum_{i=1}^N \frac{(\sigma_{\text{obs}}(i) - \sigma_p(R_i))^2}{\sigma_{\text{error}}^2(i)}, \quad (6.4)$$

where N is the number of data points constraining the fit and n is the number of free parameters, $\sigma_{\text{obs}}(i)$ is the observed value of sigma at a radius, R_i , $\sigma_p(R_i)$ is the projected dispersion of the model at R_i and σ_{error} is the uncertainty of the observation belonging to that radius.

To evaluate the goodness of fit, we compared the models to the new integrated-light dispersions and the PNe dispersion presented in this paper. In our fit, we excluded the aberrant point at ~ 2.5 kpc and we used the combined values for slits 2 and 3. The best value for our merit function corresponded to a model with $\beta_0=0.175$, $\Gamma=12M_{\odot}/L_{\odot}$, $a=12.25\text{kpc}$, and $\sigma_{\text{DM}}=375\text{km s}^{-1}$. The best model is shown in Fig. 6.11.

Despite the inherent simplifications and assumptions in this model, it presents a realistic physical description that is consistent with observations and theory. The observations presented in Fig. 6.8 show slightly radial orbits in the center that become more tangential in the outer parts.¹ As shown in Fig. 6.12, the anisotropy of our models becomes more difficult to distinguish at large radii, but in the central parts the best model is consistent with the radial properties of the observations.

Hernquist & Quinn (1987) predict a core radius of 2-4 R_e (8.7-17.3 kpc) for NGC 3923. Our mass-to-light ratio of $12M_{\odot}/L_{\odot}$ lands at the high end of values measured for other galaxies (see §5.3.2.4 and Table 4.25 in Binney & Tremaine (2008)).

The fractional dark matter content of NGC 3923 shown in Fig. 6.13 falls slightly lower than estimates of 10-50% within $1R_e$ (4.3kpc) and 75-90% at $5R_e$ (21.5kpc) (Gerhard et al. 2001; Napolitano et al. 2005; Cappellari et al.

¹These observations confirm the reality of anisotropy changing as a function of radius. Due to the degeneracy between mass and anisotropy, we recognize the importance of orbital structure in dynamical modeling. The models in this work are intended to be simple, and a more sophisticated approach would certainly require a more flexible anisotropy profile.

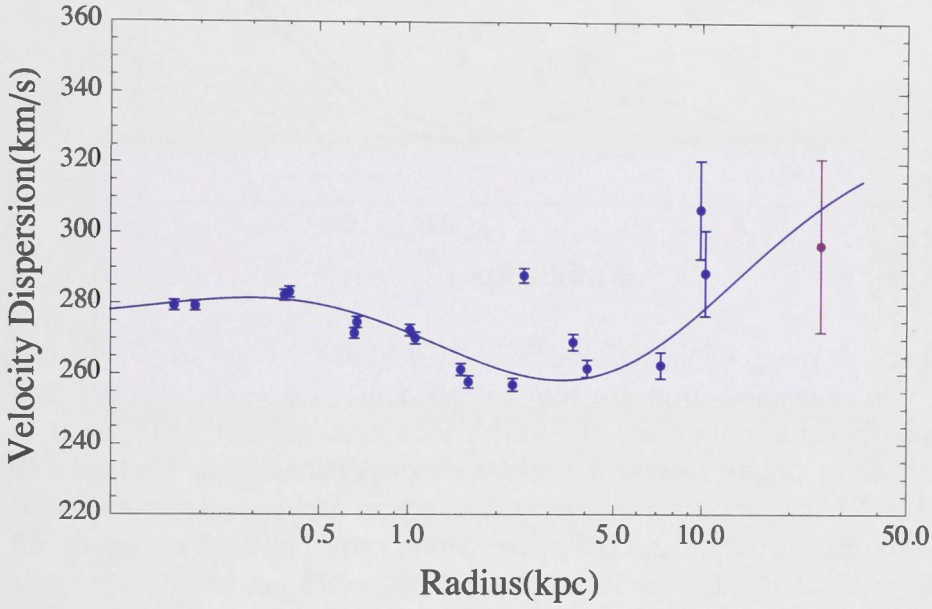


Figure 6.11 Jeans model of NGC 3923. The blue points are the major axis measurements discussed in §6.2.5.2. The PN dispersion measurement, shown as a red point, is calculated using the robust technique and the instrumental error has been removed. The model with the best goodness-of-fit value is shown next to the data. It corresponds to a spherical Jeans model including a pseudo-isothermal DM distribution and with $\beta_0=0.175$, $\Gamma=12M_\odot/L_\odot$, $a=12.25\text{kpc}$, and $\sigma_{\text{DM}}=375\text{ km s}^{-1}$.

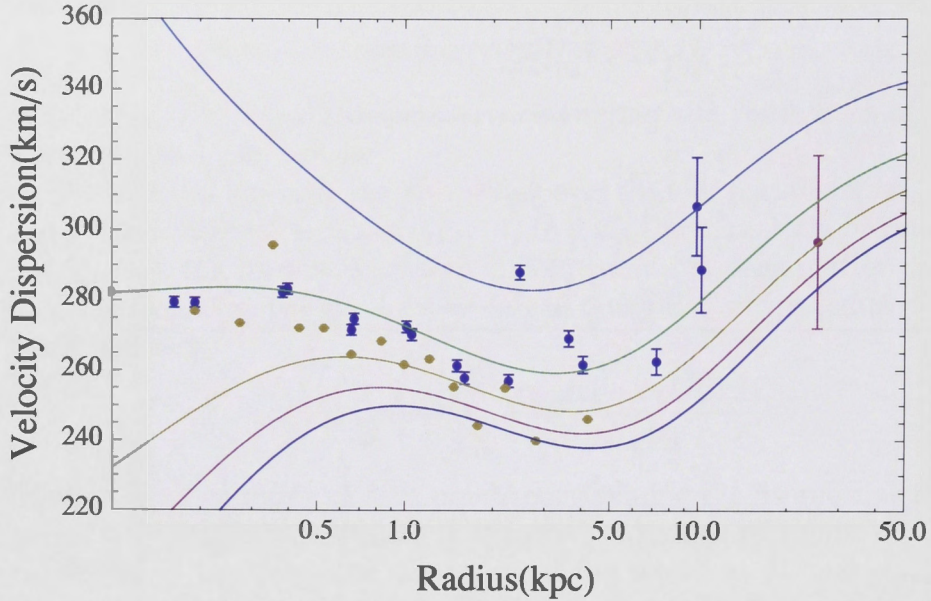


Figure 6.12 A range of Jeans models of NGC 3923. These models cover a range of anisotropies: from bottom to top $\beta = -1.0, -0.6, -0.2, 0.2, 0.6$. As before, the blue points are the major axis measurements discussed in §6.2.5.2. Yellow points represent major-axis dispersions from Carter et al. (1998). The PN dispersion measurement, shown as a red point, is calculated using the robust technique and the instrumental error has been removed. All models have $\Gamma=12M_{\odot}/L_{\odot}$, $a=12.25\text{kpc}$, and $\sigma_{\text{DM}}=375\text{ km s}^{-1}$. Notice that the different values for β are best distinguished at small radii. As indicated in Fig. 6.11, the best fit has slightly radial anisotropy ($\beta = 0.175$).

2006; Gavazzi et al. 2007; Thomas et al. 2007; Das et al. 2010). Cappellari et al. (2006) speculated that fast-rotators may have lower dark-matter mass fractions than slow rotators. Our model of NGC 3923 is consistent with their prediction of a 30% decrease in dark matter for the fast-rotating population of early-type galaxies.

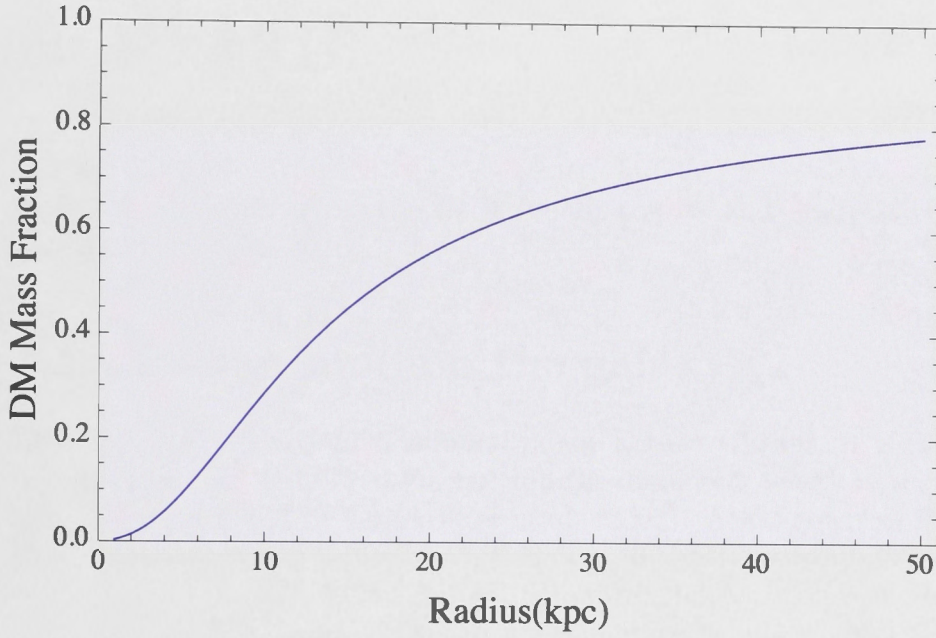


Figure 6.13 Dark matter mass fraction for NGC 3923. By considering the dark and luminous components of our model's density distribution separately, we can assess what fraction of the mass at each radius is DM. At $1 R_e$ (4.3kpc), our model is 7% dark matter. At $5R_e$ (21.5kpc), 58% of the mass is dark matter. At 50kpc ($\sim 12R_e$), the dark matter mass fraction levels off at about 78%. This plot is made for the model that best fits the kinematic data: $\beta_0=0.175$, $\Gamma=12M_\odot/L_\odot$, $a=12.25\text{kpc}$, and $\sigma_{\text{DM}}=375 \text{ km s}^{-1}$.

Chapter 7

NGC 1316

In this chapter we cover the background, results and analysis of the PN kinematics in NGC 1316.

7.1 Background on the galaxy

Like NGC 1399, NGC 1316 is found in the Fornax Cluster. It is the brightest cluster galaxy (BCG) in Fornax and the dominant galaxy in the infalling subcluster described by Drinkwater et al. (2001). Also known as Fornax A, NGC 1316 is a strong radio source (Ekers et al. 1983). It exhibits some similar properties to NGC 5128 (Cen A) (Schweizer 1980), which is the subject of one of the earliest and most successful planetary nebula surveys (Hui et al. 1995). NGC 1316 is joined by a nearby disk galaxy, NGC 1317, to its immediate North. Its distance, as measured by surface brightness fluctuations, is 21.5 Mpc (Tonry et al. 2001). The systemic velocity of NGC 1316, as measured by Longhetti et al. (1998), is 1760 km s^{-1} and that of NGC 1317 is 1941 km s^{-1} (de Vaucouleurs et al. 1991).

NGC 1316 is assumed to be the remnant of a recent merger of two disk galaxies. This is based on observations showing that it is very bright, dusty, and the central velocity dispersion is low compared to our expectation from the Faber-Jackson relation (D’Onofrio et al. 1995). According to Goudfrooij et al. (2001), the intermediate-age globular cluster system indicates that the merger event took place approximately 3 Gyr ago. NGC 1316 has twin radio lobes that are joined by a bridge. The bridge is displaced slightly from the optical center of the galaxy prompting Ekers et al. (1983) to suggest that it was formed from multiple galaxy collisions.

The dust lane along the minor axis and the clearly visible structure in the inner parts imply that this system may not yet be in equilibrium. However,

the 2MASS image is highly symmetrical and the Spitzer IRAC 3.6μ image is regular. In this work, we assume the system is in equilibrium and complete time-independent analysis. It is classified as a peculiar S0 galaxy, and its flattening is contributed to by rotation (D'Onofrio et al. 1995). As a recent merger remnant and a BCG, NGC 1316 provides a valuable example for studying the assembly of early-type galaxies.

NGC 1316 has been studied in optical, X-ray and radio wavelengths (Schweizer 1980; Kim & Fabbiano 2003; Ekers et al. 1983). Schweizer (1980) covers the B-band photometry to $450''$ (~ 70 kpc) and Fabbiano et al. (1994) provides HST B-band photometry for the central $10''$. The most recent integrated-light kinematics have been published by Bedregal et al. (2006). The globular cluster system has been studied by several groups (Grillmair et al. 1999; Gómez et al. 2001; Goudfrooij et al. 2001), but none of them has explored the kinematics. McMillan et al. (1993) and Feldmeier et al. (2007) published catalogs of PNe in NGC 1316 and Arnaboldi et al. (1998) presented a sample of 43 PNe that included velocity measurements.

7.2 NGC 1316 PN velocity catalog

7.2.1 Observations

The planetary nebula kinematics of NGC 1316 were measured using counter-dispersed spectroscopy with FORS2 on the VLT (Appenzeller et al. 1998). As shown in Fig. 7.1, NGC 1316 was covered with 7 fields, which were observed on 3-5 November 2002. The observing conditions are summarized in Table 7.1.

The FORS field-of-view is $6'.8 \times 6'.8$ or 42.5 kpc on each side at 21.5 Mpc for NGC 1316 (Tonry et al. 2001). The spatial scale is $0''.25$ /pixel.

We used the 1400V grating with a measured mean dispersion of $0.63\text{\AA}$ pix^{-1} . The arclines in the calibration frames have an average FWHM of $2.25\text{\AA}$ (135km s^{-1}). An interference filter, FILT_503.5+86, was used to select emission at the wavelength of the redshifted [OIII] line. The filter prevents spectra of continuum sources from overwhelming the field, and it allows $> 50\%$ -transmission detection of PNe in the range of -720 to 2280 km s^{-1} .

In counter-dispersed spectroscopy, the field is first imaged with a grism in the light path. This causes continuum sources such as stars to appear as streaks in the direction of dispersion. Emission-line objects such as planetary nebulae appear as dots. Another exposure is taken with the position angle (P.A.) rotated 180° . The distance between the emission line objects detected in the P.A.=0 and P.A.=180 frames is a function of the object's velocity.

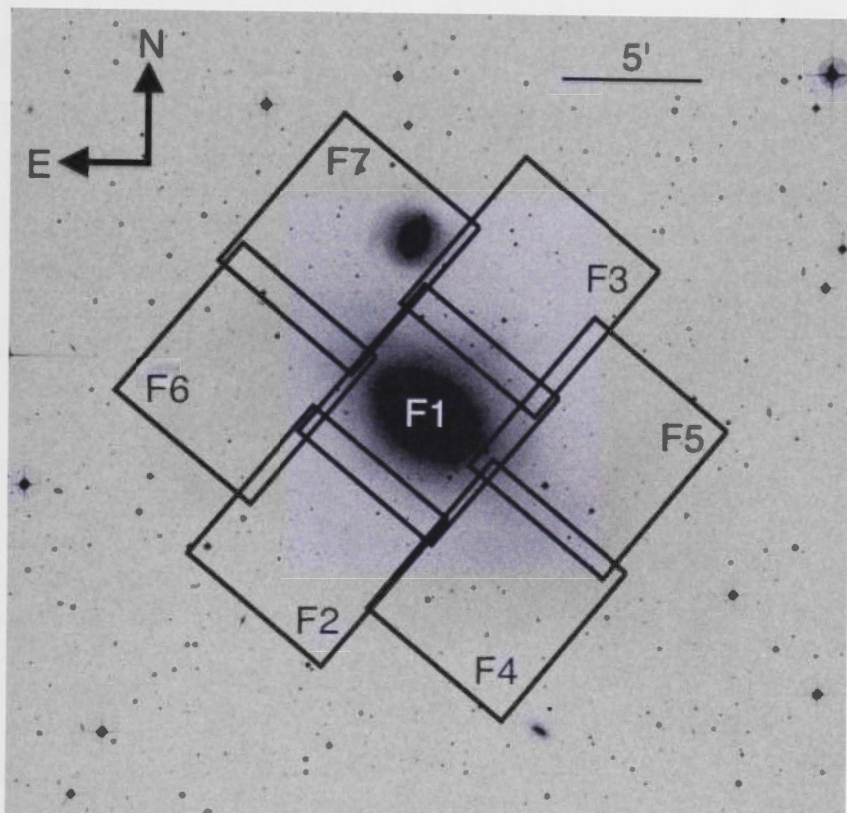


Figure 7.1 DSS image of NGC 1316 showing the approximate positions of the seven fields observed. NGC 1316 sits at the center of Field 1 and NGC 1317 is visible in Field 7. The fields are oriented along the major axis of NGC 1316. The actual observed area is slightly smaller because the two counter-dispersed exposures of each field do not overlap completely.

Table 7.1 Observing log for NGC 1316*.

Field	R.A. (J2000)	Dec. (J2000)	P.A. Label	Exp. Time (s)	Seeing (FWHM)
NGC1316-1	03:22:41.8	-37:12:32.1	W140	4 × 1080	1.2''
NGC1316-1	03:22:41.6	-37:12:29.9	E230	4 × 1080	1.3''
NGC1316-2	03:23:00.5	-37:16:59.7	W140	4 × 1080	1.0''
NGC1316-2	03:22:53.6	-37:16:59.8	E230	4 × 1080	1.1''
NGC1316-3	03:22:23.0	-37:08:04.9	W140	4 × 1080	1.0''
NGC1316-3	03:22:23.1	-37:08:04.0	E230	4 × 1080	1.2''
NGC1316-4	03:22:28.9	-37:18:58.1	W140	4 × 1080	0.9''
NGC1316-4	03:22:28.9	-37:19:00.0	E230	4 × 1080	1.0''
NGC1316-5	03:22:10.1	-37:14:02.8	W140	4 × 1080	1.1''
NGC1316-5	03:22:10.1	-37:14:02.2	E230	4 × 1080	1.1''
NGC1316-6	03:23:13.5	-37:11:01.2	W140	4 × 1080	1.2''
NGC1316-6	03:23:13.5	-37:11:01.0	E230	4 × 1080	1.1''
NGC1316-7	03:22:54.8	-37:06:35.6	W140	4 × 1080	0.8''
NGC1316-7	03:22:54.9	-37:06:34.9	E230	4 × 1080	0.9''

* Each field is observed at P.A.=140° and 230°, labeled W140 and E230 respectively. Coordinates reflect the pointing of the telescope.

In our discussion of counter-dispersed-spectroscopy, the direction of dispersion is along the horizontal axis (x -axis). Both the x - and y -axes contain spatial information due to the slitless technique. The grism causes an anamorphic distortion in the focal plane including contraction in the direction of dispersion. Detailed information on the reduction techniques used for this data is found in §2.1.2, §5.2.2, and McNeil et al. (2010).

7.2.2 Cataloging and isolating the planetary nebulae

The observations of NGC 1316 were reduced and registered using similar techniques to those used for NGC 1399 and NGC 3923 detailed in §2.1.2, §5.2.2, and McNeil et al. (2010). By blinking two counter-dispersed, registered images, we are able to detect PNe. A good candidate is detected as a pair of emission-lines sources of approximately the same brightness and at the same y -position. The transmission of the filter must encompass the separation of the objects. We can improve the completeness of the catalog by making independent attempts at detection a few days or weeks apart.

The observations for NGC 1316, like those for NGC 3923, were done using FORS2. In this way, they differ slightly from the NGC 1399 observations done on FORS1. FORS2 allows a more effective calibration set-up where a regular grid of holes is drilled into the calibration mask to replace the series of slitlets used for NGC 1399 (see §5.2.2). We follow the same procedure for distortion correction and registration as in §5.2.2, but the y -positions of the calibration points are easier to measure because they are less vertically extended.

The astrometry was performed following the steps described in §5.2.5. The position of each PNe is taken to be the mean of the detections in the two counter-dispersed exposures. The astrometric solution is based on the measured positions of the stars and the coordinates of the corresponding objects in the USNO-B catalog (Monet et al. 2003). The uncertainty in these positions includes the difficulty of measuring bandpass-shifted continuum sources, but, based checks in §5.2.5, it is dominated by the $0''.3$ uncertainties on the USNO-B coordinates.

7.2.2.1 Velocity calibration

Because the FORS2 data is much easier to calibrate, there are no suspicions that the velocity calibration is wrong in either a relative or an absolute sense. To verify the agreement between the 7 fields, we matched duplicate detections in the areas of overlap. We found a total of 76 duplicated PNe, mostly from the fields that were vertically adjacent (Fields 1 & 2, Fields 1 & 3, Fields 4 &

5, Fields 6 & 7). In these four cases, the measured shift between the fields was the same size or smaller than the standard deviation of the measurements, so it was not applied. The rms of the differences in the pairs was 42km s^{-1} . We estimate the observational error of this sample to be $42/\sqrt{2} \approx 30\text{km s}^{-1}$.

To confirm the absolute velocity calibration, we compared our catalog to previously measured PN velocities from NGC 1316. The 43 PN velocities measured by Arnaboldi et al. (1998) are a subset of the 105 PNe detected by McMillan et al. (1993). Feldmeier et al. (2007) also detected 45 PNe in NGC 1316 of which 4 overlapped with the McMillan catalog, however the velocities were not measured. We find 23 PNe in common between the the current sample and those presented by Arnaboldi et al. (1998). The median difference between our measurements and the ones from Arnaboldi et al. (1998) is 1.08km s^{-1} . The scatter in the difference is 70.7km s^{-1} which is roughly expected from adding the errors of the two samples in quadrature (30km s^{-1} and 60km s^{-1}). We conclude that our absolute velocity calibration is reliable. The differences are plotted in Fig. 7.2.

7.2.2.2 Decomposing the NGC 1316 and NGC 1317 populations

The NGC 1316 PN sample shows localized contamination from the nearby Fornax galaxy NGC 1317. It is a SABa galaxy almost directly North of NGC 1316. Their projected separation is $377''$, and their systemic velocities are only 181km s^{-1} apart (Longhetti et al. 1998; de Vaucouleurs et al. 1991). Due to NGC 1316's rotation, the velocity separation near NGC 1317 is even less. Although it is a much smaller galaxy, we expect there to be contamination from NGC 1317 in the field that covers its nucleus, Field 7. The decomposition was applied to Field 7 only because it is the only field significantly influenced by NGC 1317. The decomposition of the NGC 1316 and NGC 1317 samples follows a similar two-fold membership-assignment technique to the one described in §5.2.4.6 for NGC 1399 and NGC 1404.

Velocity criterion. The first criterion for membership is based on velocity. Because the velocity separation is so small and NGC 1317's systemic velocity is so near the edge of the filter, we considered the shape of the filter to be significant in shaping the overall velocity distribution. Using a maximum-likelihood technique, we fit the Field 7 velocity distribution with a sum of two Gaussians (representing the two galaxies) multiplied by a Gaussian (representing the filter). The fit to the velocity distribution is shown in Fig. 7.3. The two peaks of the fit are found at 1826.86km s^{-1} and 1936.08km s^{-1} compared to the observed values of 1760km s^{-1} and 1941km s^{-1} (Longhetti et al. 1998; de Vaucouleurs et al. 1991). Accounting for rotation in the outer parts of NGC 1316, we find this fit is consistent with our physical

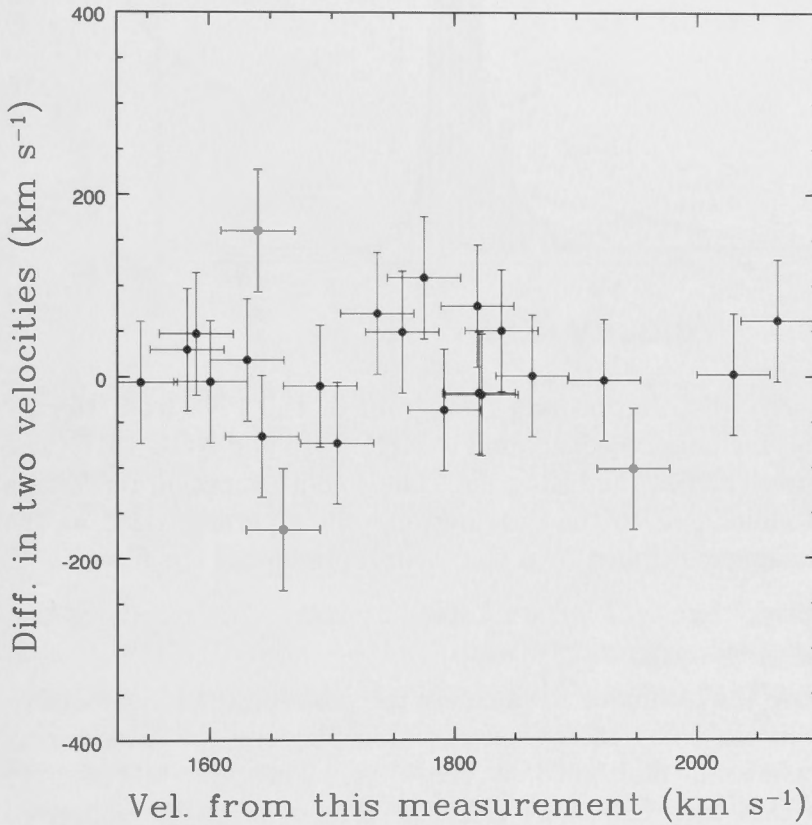


Figure 7.2 Comparison of velocities in this catalog and the sample from Arnaboldi et al. (1998) for the 23 PNe in common. On the vertical axis, the previous measurement has been subtracted from the newer one. The median difference is 1.08 km s^{-1} . The scatter in the differences (70.7 km s^{-1}) is explained by adding the errors of the two samples in quadrature. We conclude that the difference between our measurement and the previous ones is insignificant and our velocities are calibrated on an absolute scale.

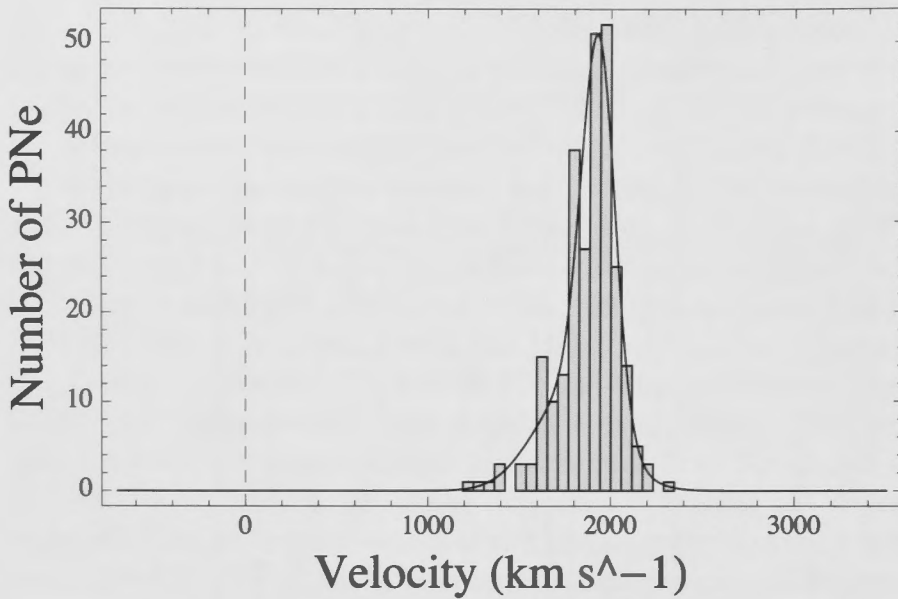


Figure 7.3 Velocity distribution and histogram of the PNe from the F7 observations. This includes objects bound to NGC 1316 and NGC 1317. The velocities are represented in the histogram. The smooth function represents the maximum-likelihood fit to the distribution— it is parametrized as the sum of two Gaussians multiplied by a Gaussian representing the filter.

understanding of the system.

We then reverse the technique to calculate the probability of membership of each velocity in the NGC 1316 Gaussian multiplied by the filter versus the NGC 1317 Gaussian multiplied by the filter. The probabilities were normalized such that each PNe must either be a member of one galaxy or the other. The probability of membership in NGC 1316 defines our velocity membership criterion.

Spatial criterion. For the spatial criterion, we project our PNe onto the major axes of the two galaxies and estimate the light contributions from each galaxy at the location of each PN. We can use this selection method because PNe trace the stellar light (Cocato et al. 2009).

We estimate the major-axis radius of each PN assuming a fixed ellipticity of $\epsilon=0.33$ based on isophotes from the DSS image of NGC 1316 and $\epsilon=0.17$ for NGC 1317 based on measurements by Wozniak et al. (1995). The position angle of NGC 1316 is assumed to be constant at 50° . For NGC 1317, we estimate P.A.= 150° based on Fig 2 in Wozniak et al. (1995), but this is only valid because we are interested in values outside $\sim 16''$.

We compared the light contribution from each galaxy by using the B-band

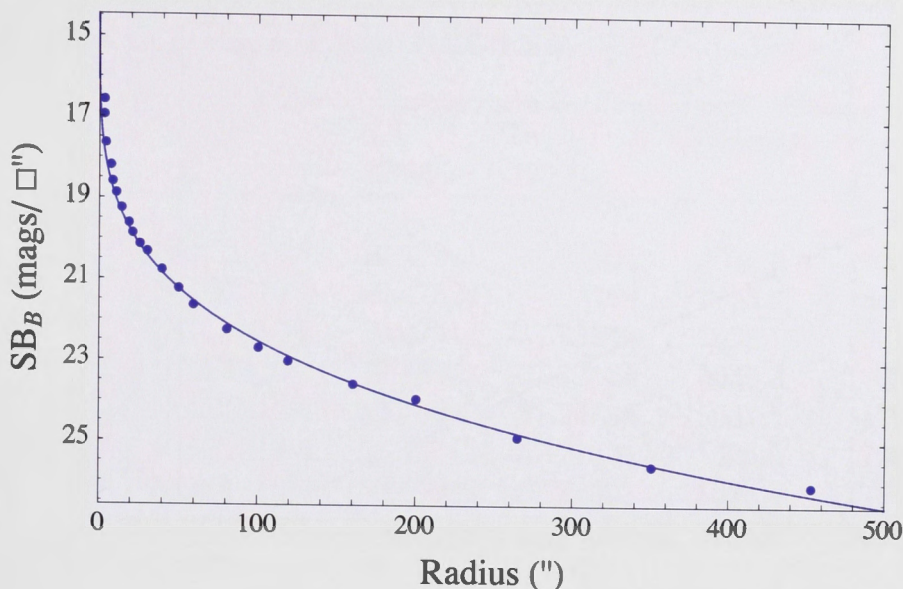


Figure 7.4 Surface brightness profile of NGC 1316. The dots show B-band observations from Schweizer (1980). The line is a Sersic fit to the outermost 14 observations. This provides a realistic extrapolation of the data for the range where the surface brightness is not observationally constrained.

light profiles from Schweizer (1980) for NGC 1316 and Wozniak et al. (1995) for NGC 1317. To estimate the surface brightness profile beyond the limits of these observations, we fit the outermost 14 observations from Schweizer with a Sersic profile and the outermost 15 observations from Wozniak et al. with an exponential profile. The fits are shown in Figs. 7.4 and 7.5 respectively. The probability of membership based on position is the ratio of the stellar light contributed by NGC 1316 to the total stellar light at the location of each PN ¹.

Selection of the NGC 1316 sample. To select the final sample for NGC 1316, we multiplied the velocity and spatial criteria. The final probabilities are normalized such that the total probability of membership for each object is one. However, objects are assigned membership in a galaxy only if they have more than 90% probability of belonging. This yields a catalog of 796 PNe bound to NGC 1316. 69 PNe are members of NGC 1317 and 43 are ambiguous.

¹This criterion relies on the assumption that NGC 1316 and NGC 1317 have the same luminosity specific number density. Since both of these systems have relatively young PN populations, this is a safe assumption.

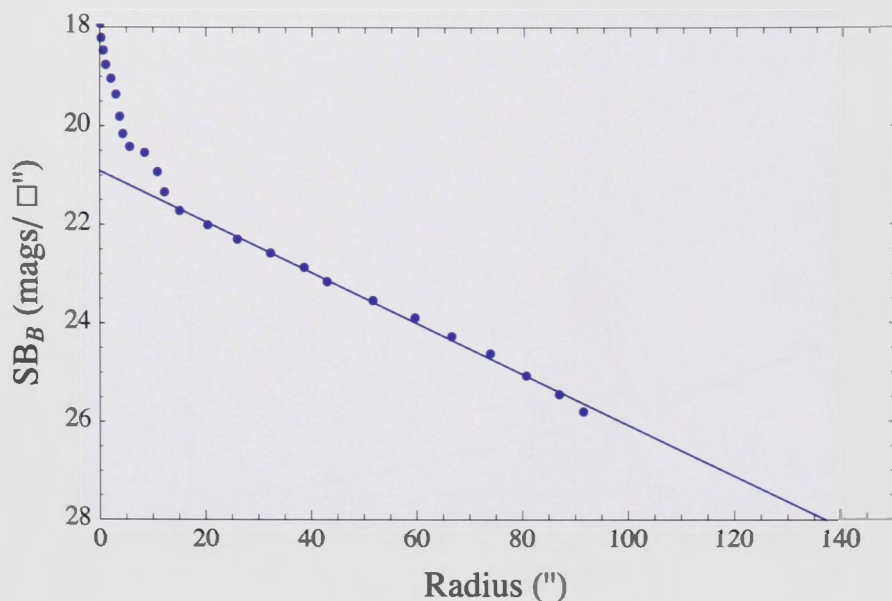


Figure 7.5 Surface brightness profile of NGC 1317. The dots are the B-band measurements from Wozniak et al. (1995). The outermost 15 points have been fit with an exponential model under the assumption that, at large radii, the disk's light is dominating the profile of this SABa galaxy.

7.2.2.3 Contamination from other sources

Based on the two-fold decomposition technique in §7.2.2.2, we are able to identify and remove PNe that belong to nearby galaxies. Our samples also include potential contamination from other sources. Since NGC 1316 shows signs of being a recent merger, there may be HII regions appearing as emission-line sources, but unlike a PN, they will be associated with (usually detectable) continuum. Most background galaxies can be identified as non-planetary nebulae because they are associated with continuum, they are spatially extended or they have double emission lines. Some emission-line sources cannot be distinguished from PNe— they are most likely unresolved Lyman- α galaxies at $z=3.1$.

These background objects show a velocity distribution centered on the filter instead of the galaxy's systemic velocity enabling us to estimate how much contamination is present in the catalog. Refer to Fig. 5.15 for the limits of the filter. However, they are extremely difficult to remove because their spatial distribution is approximately flat over the field of view. Contamination from these background galaxies is minimized by selecting only the brightest objects to be PN candidates. In the case of the NGC 1316, contamination is limited (see Fig. 7.6) and we are confident that our results

Table 7.2 Catalog of PNe in NGC 1316

ID	RA J2000	Dec J2000	wavelength Å	v_{helio} km s ⁻¹
NGC1316 1	50.47341	-37.21804	5039.0	1924
NGC1316 2	50.47824	-37.23466	5033.4	1587
NGC1316 3	50.47914	-37.21044	5038.7	1901
NGC1316 4	50.48403	-37.22564	5035.3	1700
NGC1316 5	50.48860	-37.24886	5031.5	1472
NGC1316 6	50.48942	-37.21301	5036.9	1798
NGC1316 7	50.49080	-37.24301	5036.4	1764
NGC1316 8	50.49086	-37.20056	5033.6	1598
NGC1316 9	50.49483	-37.20033	5035.5	1713
NGC1316 10	50.49716	-37.23789	5033.2	1572
⋮	⋮	⋮	⋮	⋮
NGC1316 794	50.86464	-37.18436	5038.1	1868
NGC1316 795	50.86579	-37.18282	5039.4	1947
NGC1316 796	50.87387	-37.21063	5038.2	1876

NOTES - Details on the astrometry are in §7.2.2. Velocities are corrected to heliocentric. The velocity error is 30km s⁻¹. The full catalog will be made available with a future publication.

are insensitive to it because we employed robust methods for analyzing the kinematics.

7.2.2.4 PN catalog

The velocity histogram of 908 PNe observed in the NGC 1316 fields is shown in Fig. 7.6. This is an exceptionally large catalog. 796 of these objects are bound to NGC 1316 with greater than 90% probability. The sample also includes 69 members of NGC 1317's PN population and 43 ambiguous objects. Excerpts of the catalogs for NGC 1316 and NGC 1317 are presented in Tables 7.2 and 7.3 respectively. The full catalogs will be published in the future.

This sample contains nearly 5.5 times as many objects as the NGC 1399 sample. Since they are both members of the Fornax cluster, we assume a common distance and compute the size of a hypothetical sample for com-

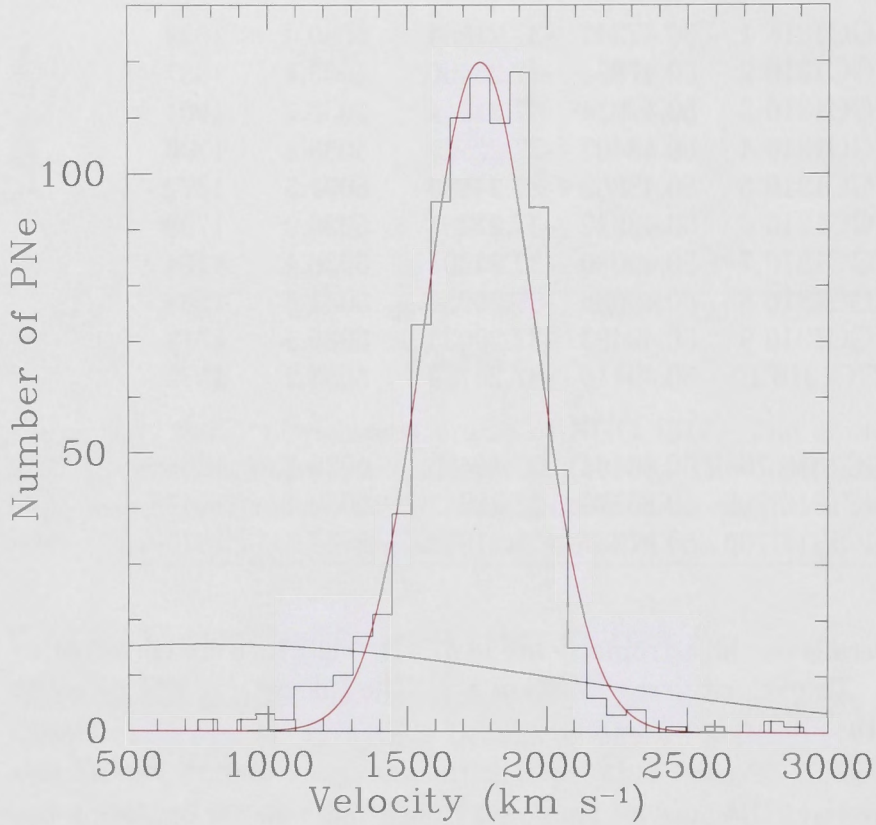


Figure 7.6 Velocity histogram of all of the PNe detected in the observations. This includes 796 objects associated with NGC 1316, 69 associated with NGC 1317 and 43 ambiguous ones. The red Gaussian has a mean of 1760 km s^{-1} and a dispersion of 200 km s^{-1} ; this is a rough estimate of the underlying distribution of the galaxy. The black curve represents the transmission of the filter. Where the transmission is high at low velocities, there is an excess of PNe in our sample compared to the Gaussian. Despite the relatively small size of the sample (only 69 objects), a second peak is visible near the systemic velocity of NGC 1317 (1941 km s^{-1} according to de Vaucouleurs et al. 1991).

Table 7.3 Catalog of PNe in NGC 1317

ID	RA J2000	Dec J2000	wavelength Å	v_{helio} km s ⁻¹
NGC1317 1	50.65941	-37.09871	5039.8	1970
NGC1317 2	50.66192	-37.09394	5040.7	2026
NGC1317 3	50.66277	-37.10502	5040.3	1998
NGC1317 4	50.66303	-37.10728	5041.5	2072
NGC1317 5	50.66341	-37.10949	5040.1	1989
NGC1317 6	50.66537	-37.08525	5039.6	1956
NGC1317 7	50.66625	-37.09976	5041.6	2081
NGC1317 8	50.66925	-37.10303	5039.5	1951
NGC1317 9	50.66943	-37.08724	5039.1	1927
NGC1317 10	50.66995	-37.10643	5039.5	1954
⋮	⋮	⋮	⋮	⋮
NGC1317 67	50.71118	-37.09235	5039.2	1933
NGC1317 68	50.71183	-37.09738	5039.3	1938
NGC1317 69	50.72124	-37.10676	5039.1	1926

NOTES - Details on the astrometry are in §7.2.2. Velocities are corrected to heliocentric. The velocity error is 30km s⁻¹. The full catalog will be included in a future publication.

parison with the one observed in NGC 1316. Beginning with the 146 PNe in NGC 1399, we add 55 objects based on symmetry arguments to account for the 4 of 9 fields that were not observed. We scale by 2.42 to account for the difference in brightness. For this we used 2MASS (Skrutskie et al. 2006) K magnitudes adjusted according to Kormendy & Tremaine (2011). Finally, we follow the relation from Hui et al. (1993) modifying the PN number density for the color of the galaxies. This accounts for a factor of 1.9, and it is a lower limit since NGC 1316 is dusty and its color may be reddened. Adjusting for these differences in the situation, we can compare our sample of 796 PNe in NGC 1316 to a hypothetical sample of 924 PNe. We conclude that, although NGC 1316 has a remarkably large sample, it is not unreasonable or even unexpected.

7.2.3 Kinematics of NGC 1316

Our analysis of the PN kinematics hinges on the assumption that PNe trace the same population as the stellar light. Coccato et al. (2009) showed this for a sample of elliptical galaxies observed on the PN.S. In Fig. 7.7, we show a comparison of the B-band stellar surface brightness and the PN number density. The PNe were divided into annular bins and the logarithmic number density in each bin was computed as

$$\rho_{\text{PNe}} = -2.5 \log_{10}(N_{\text{PNe}}/A) + c,$$

where N_{PNe} is the number of PNe in that bin, A is the area of the annulus and c is an arbitrary constant chosen for the galaxy (but remaining the same for all the bins). In this case, $c = 17.17$.

The first bin of PNe is incomplete due to the limit of detectability near the center of the galaxy. The two surface brightness profiles show good agreement until $\sim 250''$ where the influence of dust becomes apparent. Dust strongly affects the integrated light observations², as apparent in the disagreement between the three measurements of the major-axis surface brightness profile. The NE major axis is the least affected by dust and, therefore, the best point of comparison for the PNe.

In the region where the PN sample is complete and dust does not obscure the B-band integrated light, the PNe number density shadows the NE major-axis surface density of the stars. We conclude that the PNe and the integrated

²PN detections are also affected by the dust, but the profile in Fig. 7.7 compares annular bins of PNe (which are robust) to integrated-light measurements from cones along the major axis (which are vulnerable to extinction as they traverse lanes and clumps of dust). Therefore, we expect the dust to have a stronger impact on the integrated light observations than the PN number density profile.

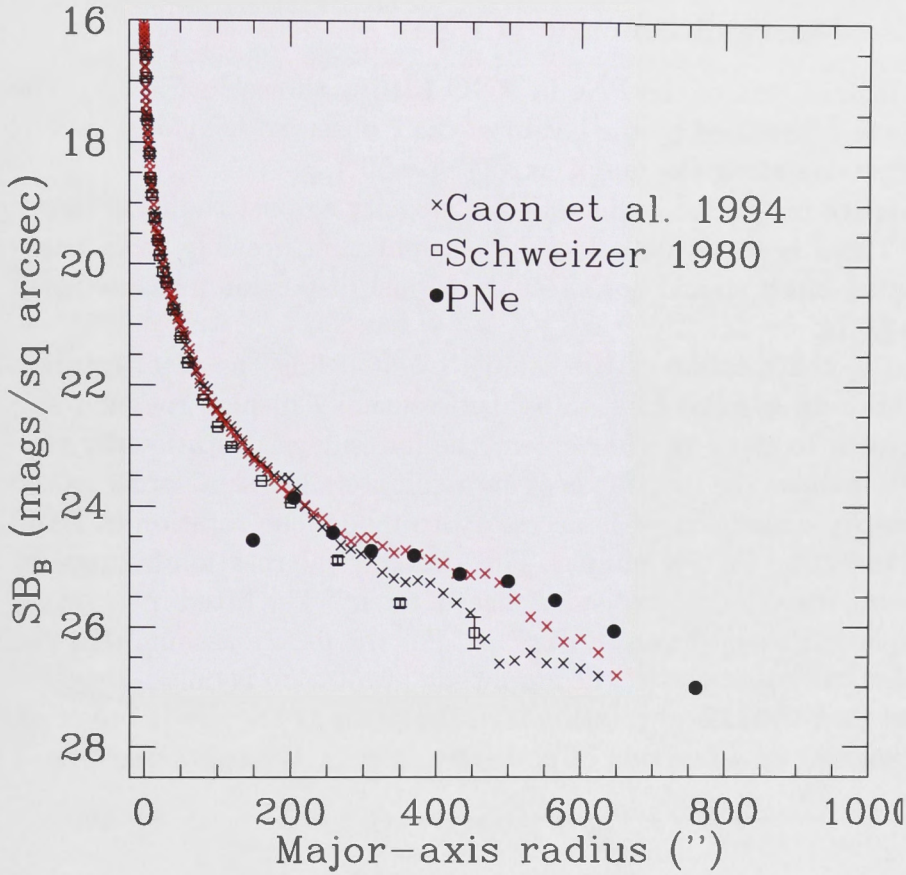


Figure 7.7 Surface density profiles for the PNe and stars in NGC 1316. Red and black crosses mark the NE and SW major-axis B-band surface brightness profile of NGC 1316 respectively (Caon et al. 1994). The hollow squares show the measurements from Schweizer (1980). In the outer parts, the logarithmic number density of PNe in annular bins is shown with black dots. The first bin of PNe is not complete and falls below the relation. The PNe follow the light distribution until at least 500". Dust in the outer parts makes the integrated light measurements more difficult as shown by the disagreement between the three profiles (positive and negative major axes from Caon et al. and those from Schweizer). The red crosses show the least dust extinction. The agreement with the NE major axis between 200" and 500" indicates that the PNe do trace the light, except where dust obscures our observations.

light are compatible tracers of the underlying stellar mass. We will use the two tracers together to constrain dynamical models of NGC 1316 in §7.3.

7.2.3.1 Phase-space distribution of PNe

The spatial distribution of the PNe in NGC 1316 is shown in Fig.7.8. The overall shape is determined by the layout of the 7 observed fields in Fig. 7.1, and we see rotation along the major axis (P.A.=50°).

A phase-space projection of line-of-sight velocity against radius is shown in Fig.7.9. There is some low-velocity contamination possibly from background galaxies, but it should not affect the robust dispersion measurements discussed in §7.14.

We quantify the rotation of the sample by modeling the total rotation and the rotation in annular bins. S0 galaxies usually display rotation and we are interested to learn to what extent the flattening is rotationally supported. Also, because the rotation is of approximately the same order as the expected velocity dispersion, it is necessary to model the rotation of NGC 1316 before analyzing the PN sample. This prevents the rotation from artificially increasing the velocity dispersion measurement. The fitted rotation for the full sample of PNe is shown in Fig.7.10. For the fit, we assume that the galaxy is spherically symmetric, the amplitude of rotation is only a function of radius and that the axis of rotation is in the plane of the sky (Côté et al. 2001). The velocity as a function of position angle, Θ , is parametrized as

$$v_p[\Theta] = V_{sys} + A \cos(\Theta - \Theta_0),$$

where V_{sys} is the systemic velocity, A is the amplitude of rotation, and Θ_0 is the P.A. of the kinematic major axis. We also considered adding a $\sin(3\Theta)$ term, but the simpler model was preferred by a Bayesian Information Criterion test.

Because we suspect a fit including a free systemic velocity to be influenced by non-PNe contaminating the center of the filter (see Fig. 7.6), we hold V_{sys} constant at 1760 km s^{-1} (Longhetti et al. 1998). The result is a kinematic major axis at P.A.= $64 \pm 8^\circ$ and an amplitude of rotation of $85 \pm 11 \text{ km s}^{-1}$. The photometric major axis is at P.A.= 50° .

Using the rotation fitted to the entire sample as an initial guess, we fitted the PNe in five circular annuli. The P.A. and amplitude of rotation are modelled for each annulus and the results are in Fig.7.11 and Fig.7.12 respectively. The position angle of the kinematic major axis is offset from the photometric major axis by about 14° , but based on the uncertainty shown in Fig. 7.11, they are consistent. The amplitude of rotation rises slightly in the outer parts. This could indicate that some PNe bound to NGC 1317 with

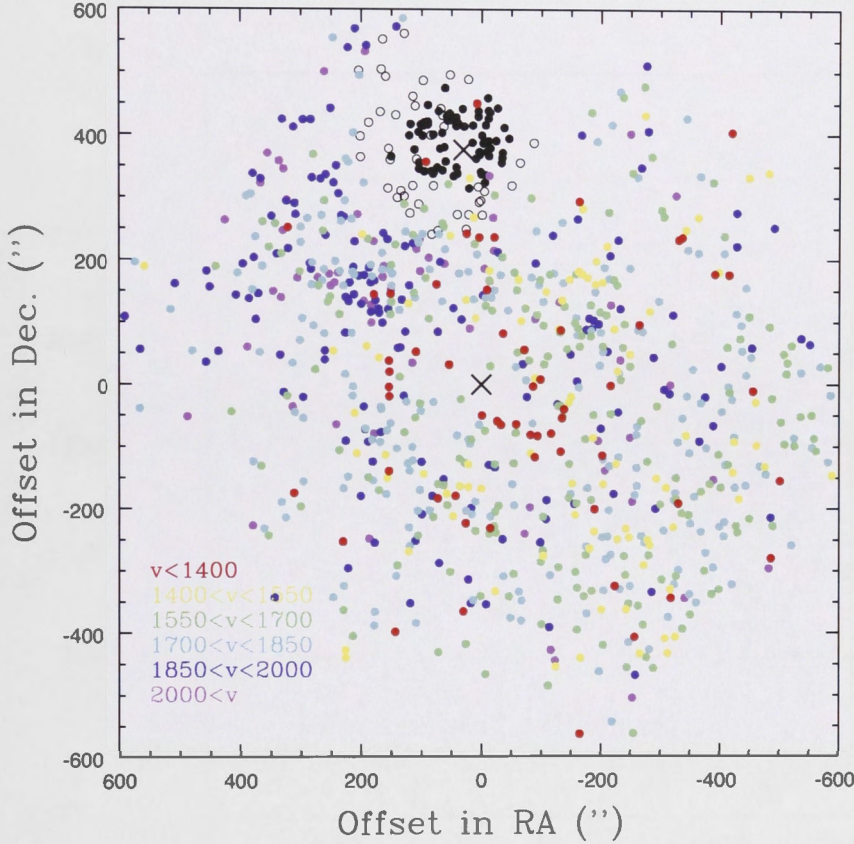


Figure 7.8 Spatial distribution of the 908 PNe in the NGC 1316 observations. North is up and East is left. The centers of the two galaxies are marked with black crosses. Surrounding NGC 1317, the solid, black dots represent PNe bound to NGC 1317 with $>90\%$ probability. The colorful dots indicate membership in NGC 1316. If a PN cannot be assigned membership with $>90\%$ probability, it is marked as ambiguous (hollow black dots). Ignoring the structure from this companion galaxy, this figure shows NGC 1316's rotation along the kinematic major axis (P.A. = 64° , see Fig. 7.11). The north-east is rotating away from the observer while the south-west is moving towards us relative to the mean.

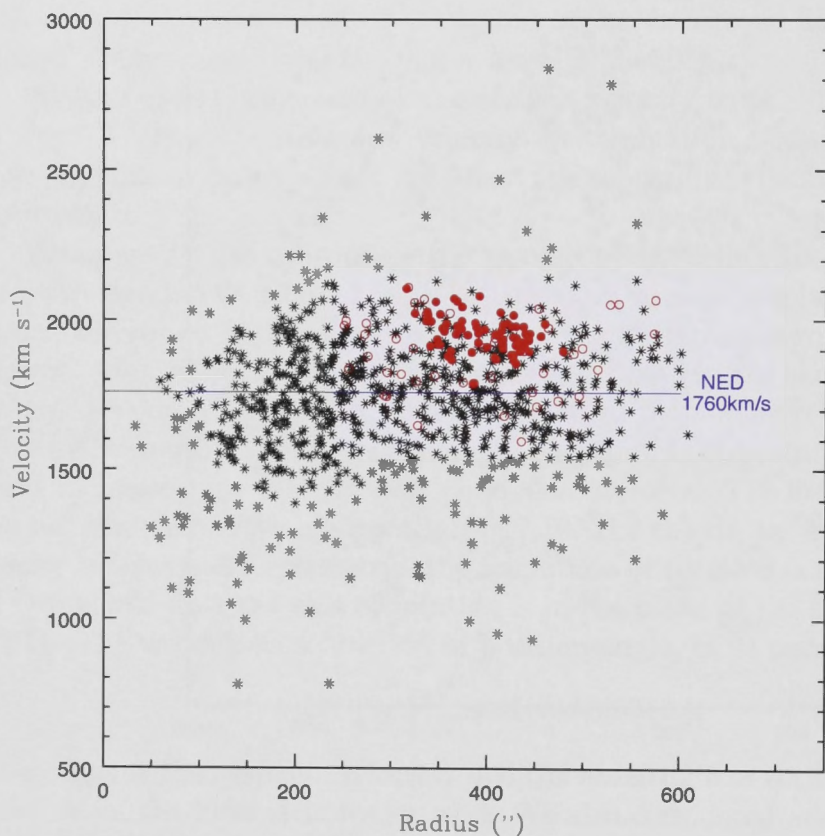


Figure 7.9 Line-of-sight velocity of the observed PNe against projected radius. The sample is centered on the systemic velocity of 1760km/s (Longhetti et al. 1998). Solid red objects have been assigned membership in NGC 1317 with >90% probability. The hollow red dots are ambiguous—they could not be assigned probability in either galaxy with more than >90% probability. There are some low-velocity objects near the center of the filter (779km s^{-1}) that may be contamination.

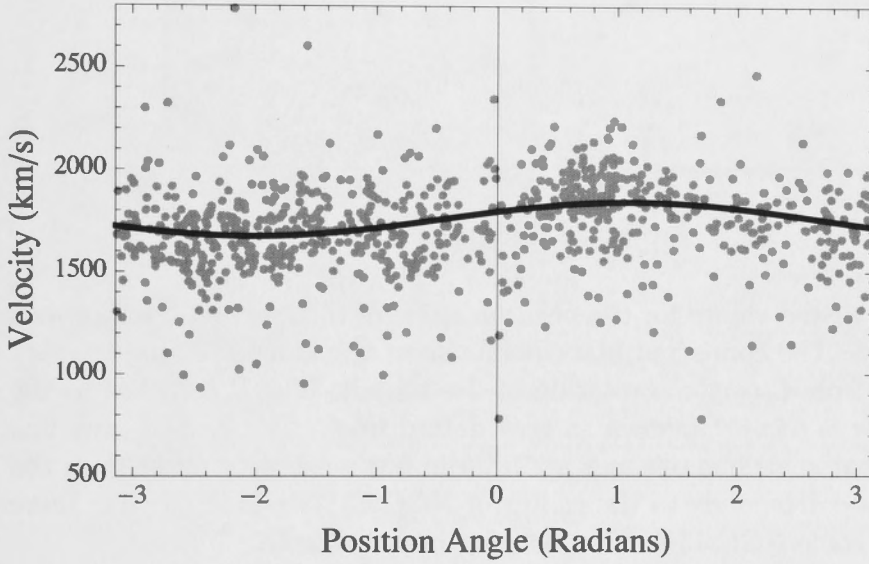


Figure 7.10 The line-of-sight velocities of the NGC 1316 PNe as a function of position angle. The grey dots represent the decomposed PNe sample. The black fit represents rotation of a spherically symmetric system with the axis of rotation in the plane of the sky. It indicates an amplitude of 81 km s^{-1} and a kinematic major axis at $\text{PA}=61^\circ$ (1.06 radians). When we hold the systemic velocity fixed at 1760 km s^{-1} , we measure the kinematic major axis at $64 \pm 9^\circ$ and the amplitude of rotation at $85 \pm 11 \text{ km s}^{-1}$.

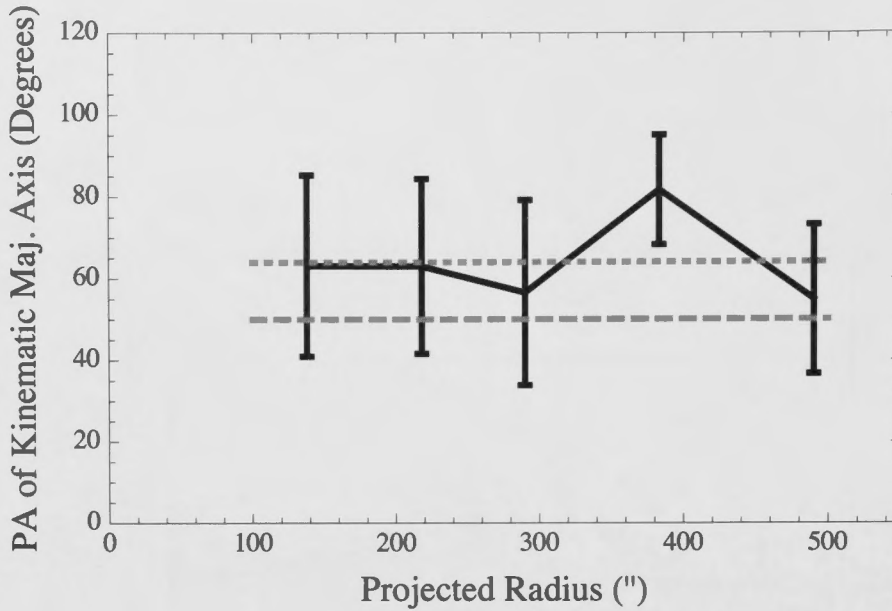


Figure 7.11 Fitted values for the position angle of the kinematic major axis of NGC 1316. The connected black points show the kinematic major axis's P.A. known from fitting the rotation in five annuli. The P.A. fitted to the entire sample is $64 \pm 11^\circ$ (shown as grey dotted line). The dashed grey line shows the photometric major axis at 50° . Bin 4 is noticeably offset from the others. This corresponds to the radius of NGC 1317 indicating that there may still be some NGC 1317 PNe included in our sample.

a systemic velocity of 1941 km s^{-1} (de Vaucouleurs et al. 1991) have stayed in our sample. The rise could also be a real description of the kinematics of NGC 1316. This phenomenon is also observed in the globular cluster system in M87 (Côté et al. 2001) (but not in the PNe, Doherty et al. 2009) and could be evidence of the outward transfer of angular momentum resulting from a merger (Quinn & Zurek 1988).

7.2.3.2 Random-motion measurements

By examining the line-of-sight velocity dispersion of a set of consistent tracers, we can sketch the total mass distribution from the central parts to the outer halo. We account for the ordered motion of the galaxy by fitting the residuals of the rotation model. For the PNe in NGC 1316, we employ a robust technique (see §5.2.7.2). This method uses only objects within 2σ of the median so it is insensitive to outliers. We iteratively reject PNe outside the cutoff and the final dispersion is scaled. Fig. 7.13 illustrates which PNe

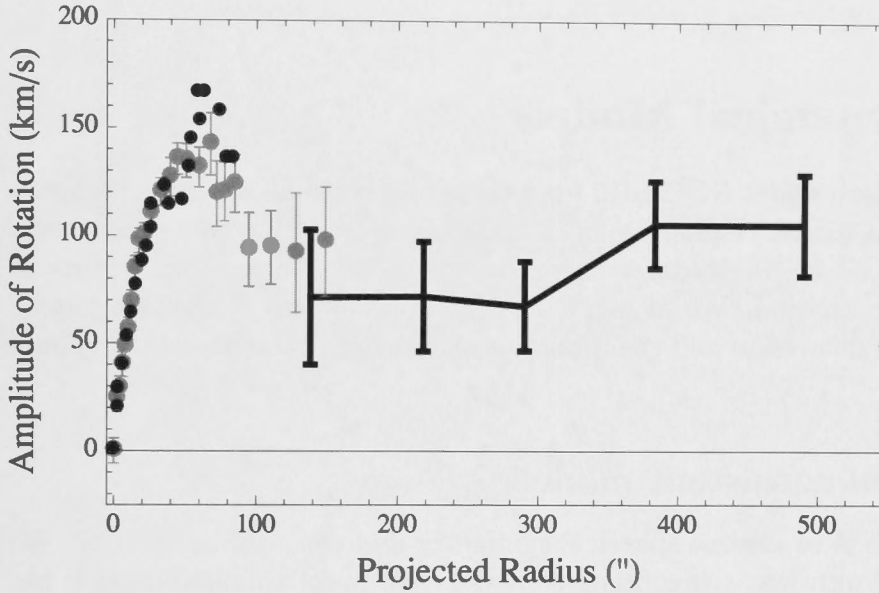


Figure 7.12 The rotation curve of the PNe in the outer parts of NGC 1316. The black line traces the amplitude of rotation of the PNe in the same annular bins shown in Fig. 7.11. At small radii, the gray dots show positive major-axis rotation measurements from Bedregal et al. (2006), and the black dots show major-axis rotation measurements from Arnaboldi et al. (1998). The rotation is increasing slightly in the outer parts— this could be indicating the outward transfer of angular momentum from a merger event (Quinn & Zurek 1988) or the influence of some NGC 1317 PNe that have remained in our sample.

were used in our final calculation. We are able to measure the v_{rms} of the PNe in a way that is resilient to possible contamination from background galaxies.

The velocity dispersion profile of NGC 1316 is shown in Fig.7.14. At small radii, the integrated-light measurements from Bedregal et al. (2006) show a falling dispersion profile. As we move into the halo, the planetary nebulae indicate that the v_{rms} continues to fall off until at least $\sim 500''$. The PNe are binned and the v_{rms} is fitted robustly.

7.3 Dynamical Models

In order to learn about NGC 1316 from these observations, we must compare the data to a model. Following the steps in §4.1 and §6.3, we create Jeans models of NGC 1316 in order to interpret the observations into a picture of the physical situation. We fit our models to observations of the integrated-light velocity dispersion and the robust measurement of the planetary nebula v_{rms} .

7.3.1 Self-consistent models

Our first step is to assume spherical symmetry and constant anisotropy. We create a non-rotating, self-consistent model. We make this assumption because the random motions dominate the rotation (as discussed in §7.3.3). Fig. 7.15 shows a model that attempts to fit the inner parts of the galaxy where the baryonic matter dominates. This model is parametrized by the mass-to-light ratio, $\Gamma = 3.7$, and the anisotropy, $\beta_0 = 0.47$. Due to the model's simplicity, it isn't possible to fit the inner and outer parts simultaneously. This indicates that additional mass from dark matter is required in the outer parts.

7.3.2 Models with dark matter

In the next model, we add in a dark matter component. The DM mass distribution is parametrized as a pseudo-isothermal halo. The model is now defined by four free parameters: β_0 , Γ , σ_{DM} , and a_{core} . With this added flexibility, we find a better fit as shown in Fig. 7.16. The model shown has a mass-to-light ratio of 3.1, a constant anisotropy of 0.525, $\sigma_{DM}=255 \text{ km s}^{-1}$ and a core radius of 10kpc

This fit was found by exploring a grid of models with resolutions of 0.005 in β_0 , 0.1 in Γ , 1 kpc in a_{core} and 5 km s^{-1} in σ_{DM} . We compared the

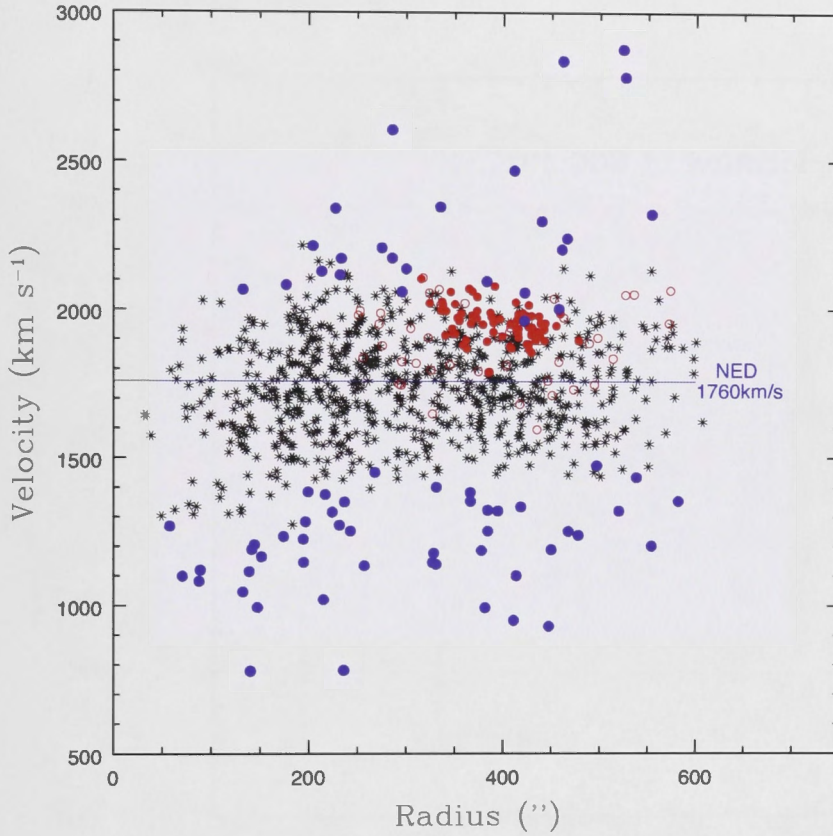


Figure 7.13 Illustration of the robust-fitting rejection sample. Here we reproduce the phase-space distribution from Fig.7.9 marking in blue those objects that were rejected during our robust fitting. Our dispersion measurements are calculated using only the black PNe on this diagram, but they are scaled to account for the trimming of the wings. The robust method is useful for samples where there may be contamination in the outer parts. Because we are applying the robust technique to the residuals of the velocity model, we are not making a rigid cut in each bin. The rejection of each object depends on its velocity and position angle.

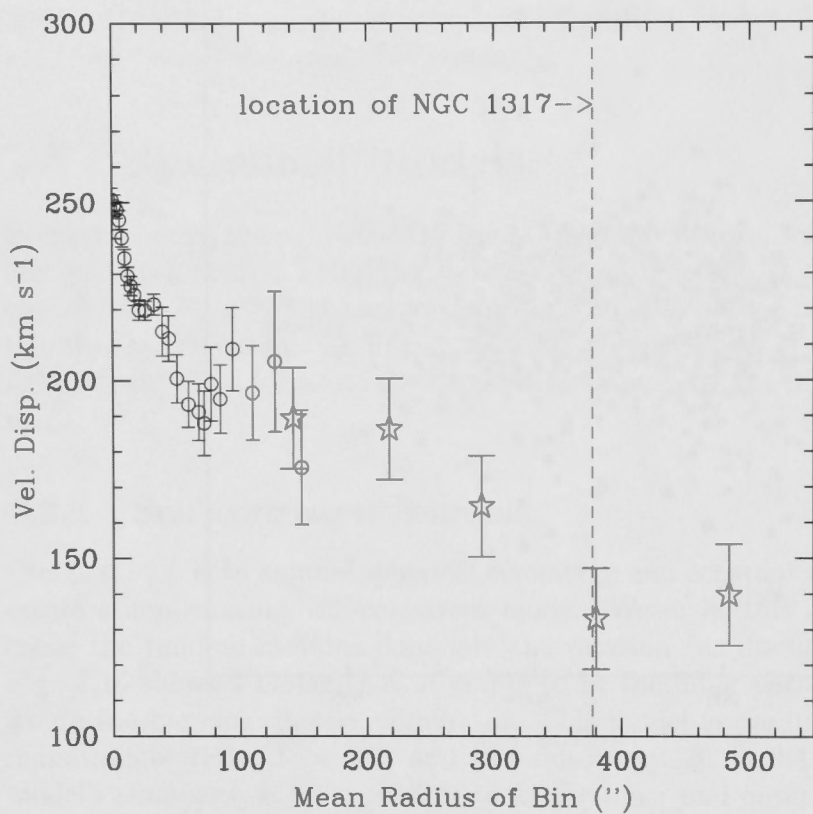


Figure 7.14 Line-of-sight velocity dispersion profile for NGC 1316. The hollow circles represent the integrated light measurements from Bedregal et al. (2006) for the major axis. The PN measurements (hollow stars) are made using the robust technique on the decomposed and rotation-corrected sample. The results should be resilient against outliers. The two tracers interface seamlessly at $\sim 150''$.

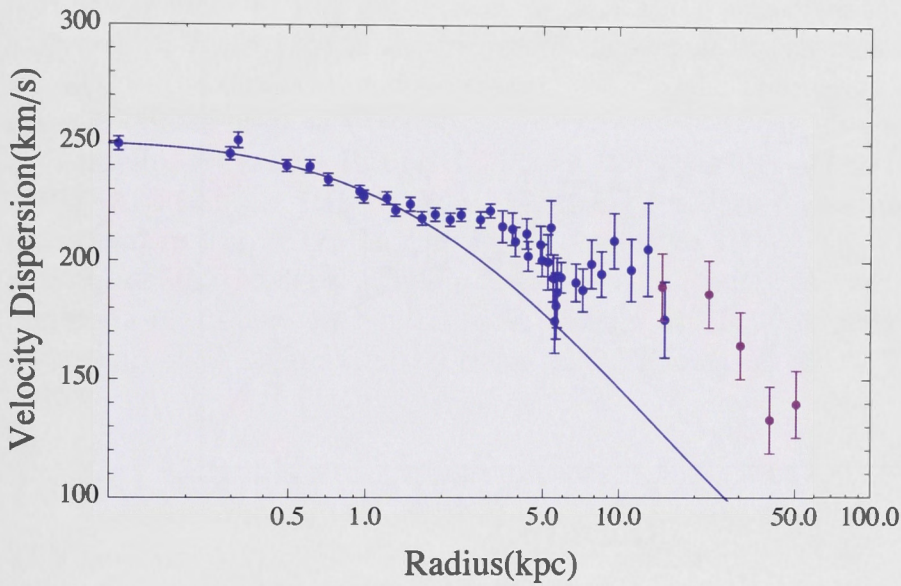


Figure 7.15 Self-consistent model of NGC 1316. The blue points show integrated-light dispersion measurements from Bedregal et al. (2006). The red points at large radii are binned PN dispersions as described in §7.14. The model has no dark matter and it does not rotate. It has a mass-to-light ratio of 3.7 and a constant anisotropy of 0.47. It does not fit the data well in the outer parts.

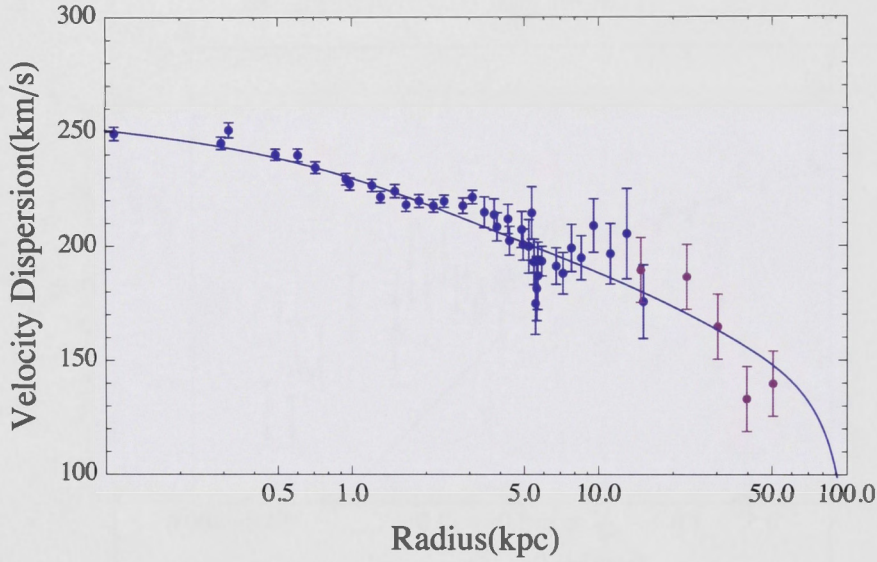


Figure 7.16 Dynamical model of NGC 1316 including a pseudo-isothermal dark matter distribution. The blue points show integrated-light dispersion measurements from Bedregal et al. (2006). The positive and negative major axes have been shifted by 0.32kpc and folded. The red points at large radii are binned PN dispersions as described in §7.14. The model has a mass-to-light ratio of 3.1 and a constant anisotropy of 0.525. The dark matter distribution has $\sigma_{\text{DM}}=255 \text{ km s}^{-1}$ and a core radius of 10kpc. This model does not rotate.

model's projected velocity dispersion profile to observations of integrated light (Bedregal et al. 2006) and the planetary nebulae. The integrated light positions were adjusted by -0.32kpc to maximize the symmetry of the dispersion profile. ³The goodness-of-fit was quantified by the expression

$$\tilde{\chi}^2 = \frac{1}{N - n} \sum_{i=1}^N \frac{(\sigma_{obs}(i) - \sigma_p(R_i))^2}{\sigma_{error}^2(i)}, \quad (7.1)$$

where N is the number of data points constraining the fit (40 in this case), n is the number of free parameters, $\sigma_{obs}(i)$ is the observed value of sigma at a radius, R_i , $\sigma_p(R_i)$ is the projected dispersion of the model at R_i and $\sigma_{error}(i)$ is the observational uncertainty of $\sigma_{obs}(i)$. The model in Fig. 7.16 has a goodness-of-fit of $\tilde{\chi}^2=1.85$.

The effective radius, R_e of NGC 1316 is 109'' (Caon et al. 1994; Goudfrooij et al. 2001). At 21.5Mpc, $1R_e=11.4$ kpc. Following the dark matter mass fraction illustrated in Fig. 7.17, dark matter comprises $\sim 31\%$ at $1R_e=11.4$ kpc and $\sim 76\%$ at $5R_e=56.8$ kpc. These values are consistent with estimates in the literature of 10-50% within $1R_e$ and 55-90% at $5R_e$ (Gerhard et al. 2001; Cappellari et al. 2006; Gavazzi et al. 2007; Thomas et al. 2007; Das et al. 2010).

7.3.3 A note about these models

This modeling technique assumes constant anisotropy. Evidence (see the h_4 measurements of NGC 3923 in §6.2.5.2) and theory agree that this is not a good assumption. The anisotropy is best fit in the inner parts where the stars dominate the mass. Assuming that the outer parts have the same orbital structure leaves our models vulnerable to a misestimation of the dark matter content. In the case of NGC 1316, our model is already quite radially anisotropic in the central regions, so it may not increase in the outer parts. If it did (or if it became quite tangential as in NGC 3923), it would change our inferred halo mass fractions.

As described by Bedregal et al. (2006) and in §7.2.3.1, NGC 1316 shows rotation in both the integrated light and the PN population. A detailed model of this system would have to account for the rotation, but the simple

³Bedregal et al. (2006) selected the peak of the dispersion profile as their position zero-point. Upon closer inspection, the highest dispersion value was an anomaly in an otherwise symmetrical profile. We removed the anomalous point and fitted the profile with a symmetrical function finding a shift of -0.32kpc relative to their system. The fit shared the same peak as the measurements (with object representing the previous zero-point removed).

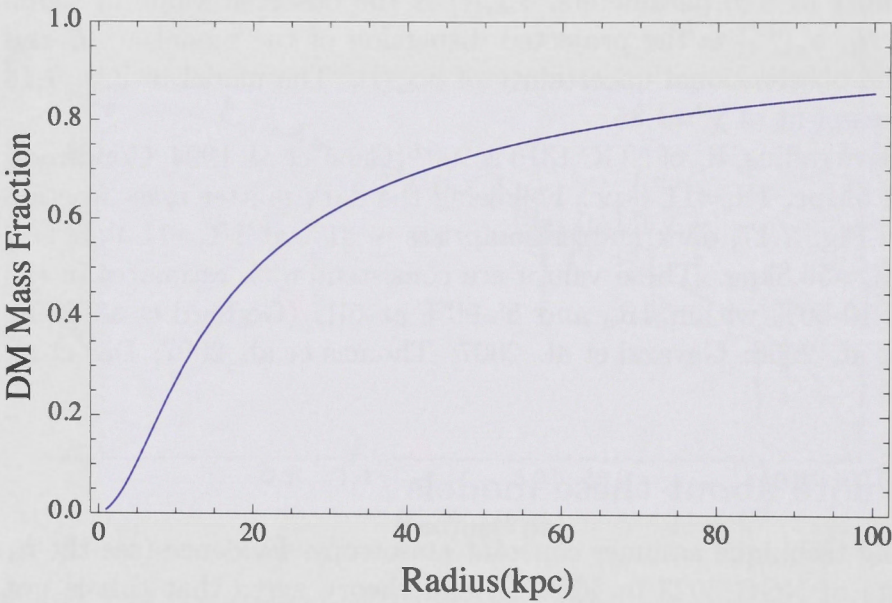


Figure 7.17 Dark matter mass fraction for NGC 1316. This plot shows the dark matter content of the model displayed in Fig. 7.16 as a function of radius. At small radii, baryonic matter dominates. At $1R_e$, 31% of the mass is dark, but at $5R_e$ the dark matter represents 76% of the total mass. In the halo, about 85% of the mass is dark. $1R_e$ is 11.4kpc for NGC 1316.

Jeans models described in this section do not. As pointed out by Bedregal et al. (2006), the random motions are larger than the rotation, so we are not surprised that the non-rotating model shown in Fig. 7.16 fits as well as it does. However, the dispersion is only marginally larger than the rotation in the outer parts, and this is the region that most interests us.

We can qualitatively anticipate the effects of including rotation in our models. In order to maintain consistency with our observed dispersions, a rotating model would need to be more massive. This would be manifested in larger values for the mass-to-light ratio, Γ , and the central density of the dark matter (translated as the parameter σ_{DM}). Since the random motions dominate, we expect these effects to be small and we account for the rotation simply by modeling the v_{rms} .

Various evidence indicates that NGC 1316 is a recent merger remnant (D’Onofrio et al. 1995; Goudfrooij et al. 2001). This raises the issue of whether this galaxy is actually in equilibrium. What impact will this have on the results of our modeling? In the outer parts of the galaxy ($\sim 500''$), we estimate that the dynamical time is an order of magnitude longer than the age of the merger (3Gyr from Goudfrooij et al. 2001). This indicates that non-equilibrium effects will be small. We would expect to see the effects of global infall or outflow as deviations from the Gaussian form of the velocity histogram. In contrast with the observations shown in Fig. 7.6, a non-equilibrium system might appear to have two peaks representing objects falling in and outflowing. On the other hand, images of NGC 1316 indicate that we might expect to see some wispy tail-like structures falling back onto the galaxy. This provides a possible explanation for the low-velocity objects appearing near the center of the filter. Overall, the observed velocity distribution supports the assumption of equilibrium in our models.

The dynamical models described above serve as a confirmation of the trends observed in dark matter distributions. The dark matter is most important in the outer parts where it represents more than 2/3 of the total mass. The anisotropy is easiest to distinguish in the inner parts of the model. In both the self-consistent and dark models, radial orbits dominate the integrated light measurements. It’s difficult to isolate the orbital structure of the outer parts of our models, but our value of $\beta_0=0.525$ is consistent with our expectation that the outer parts will tend to be radially anisotropic (Zait et al. 2008; Murphy et al. 2011).

Chapter 8

NGC 4594

In this chapter we cover the background, results and analysis of the PN kinematics in NGC 4594.

8.1 Background on the galaxy

NGC 4594 (M104, Sombrero galaxy) is an SAa galaxy (de Vaucouleurs et al. 1991) in Virgo. It is known for its bright nucleus, the clear dust lane in the disk and its prominent bulge. It is nearby (9.8Mpc, Tonry et al. 2001) and inclined nearly edge-on making it an excellent observational target.

In this chapter we will be studying the bulge and halo of NGC 4594 as a comparison point to the other early-type systems in our sample. The bulge of NGC 4594 is extremely bright— the disk contributes only 10% of the light (Burkhead 1986). It is thought that classical bulges form through mergers, and the disk settles later (Athanasoulas & Martínez-Valpuesta 2008). These kinds of bulges show many qualities that are similar to lower-luminosity ellipticals including their light-profile indices, structure, dynamics and stellar populations (Freeman 2008). Bulges represent a link between ellipticals and spirals; we can study them to understand the impact of formation processes. Thanks to the exceptionally convenient inclination of the disk, NGC 4594 presents itself as a valuable laboratory for studying classical bulges.

NGC 4594 has been well studied at many wavelengths. It was the first galaxy to have spectroscopically-detected rotation (Slipher 1914). Optical photometry has been completed by Jarvis & Freeman (1985) and Burkhead (1986). Kinematic data includes line-profile measurements taken on the KPNO 2.1-m and 4-m telescopes by Kormendy & Illingworth (1982) extending to 120'', on the 2.2-m ESO telescope at La Silla covering the inner 40'', and on the MMT and WHT by van der Marel et al. (1994) extending to

Table 8.1 Observing log for NGC 4594.

Plate	Date	Chip	Exp. Time (s)	Mean Seeing
NGC4594-1	12-13 April 1991	Thomson 3	5×2000	1."3
NGC4594-2	12-14 April 1991	Thomson 3	7×2000	1."3
NGC4594-3	13-14 April 1991	Thomson 3	8×2000	1."4
NGC4594-4	24-25 Feb 1993	Tektronix 1024	13×1500	1."4
NGC4594-5	23-24 Feb 1993	Tektronix 1024	13×1500	1."5

$\sim 45''$. NGC 4594 is a rare case of an early-type galaxy with HI observations (Faber et al. 1977; Bajaja et al. 1984). Bajaja et al. (1984) measured the circular velocity of the neutral hydrogen to be 370 km s^{-1} . The globular cluster system has been studied most recently by Larsen et al. (2002) and Bridges et al. (2007). The planetary nebulae were detected by Ford et al. (1996), but the kinematics were not measured.

8.2 NGC 4594 PN velocity catalog

8.2.1 Observations

The planetary nebula kinematics of NGC 4594 were observed using the Fibre Optic Couple Aperture Plate (FOCAP) (Gray 1984) with the RGO spectrograph on the Anglo-Australian Telescope at Siding Spring Observatory. The instrument was used with the 25cm camera and the Thomson and Tektronix 1024 chips. We used the 1200V grating with a measured mean dispersion of $0.63\text{\AA}/\text{pix}$. We cover the range $4650\text{\AA}$ to $5250\text{\AA}$ in our spectra. The arclines have a measured FWHM of $1.99\text{\AA}$.

The detection of the candidates and measurement of their positions were completed in 1990 on the CTIO 4-m telescope (Ford et al. 1996). The sample was ranked by brightness and divided into five plates where Plate 1 contains the brightest group. Plates 1, 2 and 3 were observed between 12-14 April 1991. Plates 4 and 5 were observed between 23-25 Feb 1993. The observing conditions are summarized in Table 8.1.

These observations are done with fibre spectroscopy. Using pre-determined catalogs of positions, plates are drilled with holes at the known locations of the PNe. Each hole is occupied by a fibre. The other ends of the fibres are glued into a linear configuration at the spectrograph to mimic a long slit.

The light from the fibres is dispersed and appears as a multi-object spectrum on the CCD. In these observations, there is no spatial information. One dimension along the CCD is purely wavelength. The other is aperture space where each spectrum maps to a fibre.

The advantage of fibre techniques is that the long wavelength range allows an accurate wavelength calibration. Disadvantages include light loss and restrictions due to the geometry of the holes in the plates. As with the counter-dispersed imaging data, contamination from Lyman- α galaxies at $z = 3.1$ is possible. Based on the histogram in Fig. 8.1, the NGC 4594 sample is not strongly affected by these objects.

8.2.2 Data Reduction

The data reduction was completed in IRAF using the `apextract` package. The bias-subtracted images were summed with a maximum value rejection to remove cosmic rays. The wavelength solution was based on a median of the arc calibrations which were interspersed with the science exposures. For the brightest plates, subtracting the sky introduced noise to the data. For the fainter plates, we approximated the sky by combining the 8-15 apertures with the faintest PN signal. These represent a simultaneous sky exposure. The result is a set of up to 54 wavelength-calibrated, sky-subtracted PN spectra from each plate.

The velocities of the PNe are measured by fitting the $\lambda 5007$ emission line (now shifted to the velocity of the PN) with a Gaussian. We discovered that the most reliable measurements were found by interactively fitting the line in wavelength space using `splot`. The PN velocities were corrected to heliocentric and paired with their celestial coordinates.

8.2.3 The PN catalog: positions, velocities and rotation

The five plates yielded 266 velocity measurements. An excerpt of the catalog is shown in Table 8.2, and the full table in digital format will be made available with the published version. The velocity distribution is shown in Fig. 8.1. The histogram is compared to a Gaussian ($\mu=1052\text{km s}^{-1}$, $\sigma=250\text{km s}^{-1}$). The median velocity of PN sample is 1052km s^{-1} . The subsample of PNe within $75''$ of the center of the galaxy has a mean velocity of 1024km s^{-1} , so we use that as our velocity zero-point when measuring rotation and velocity dispersion. Smith et al. (2000) also give $1024 \pm 5\text{km s}^{-1}$ as their measured recession velocity for NGC 4594.

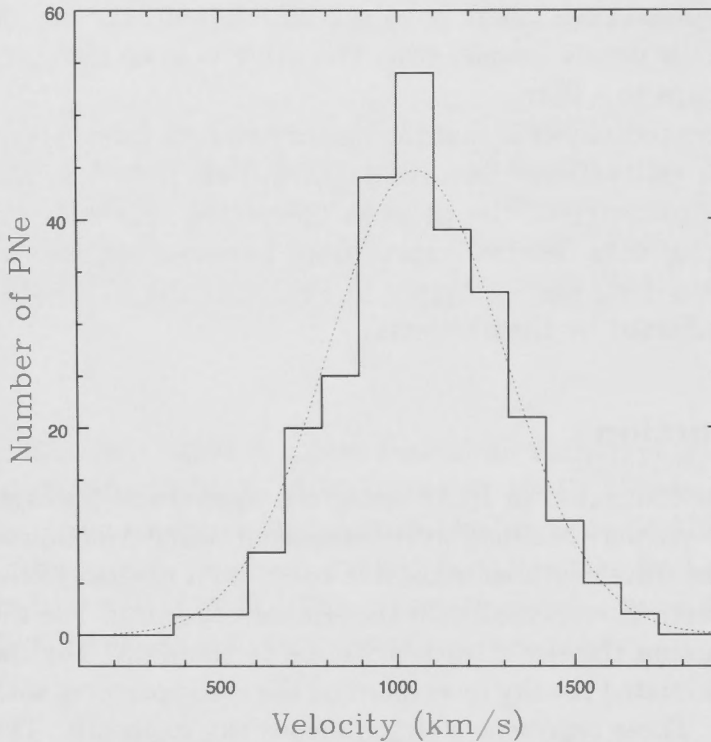


Figure 8.1 Velocity distribution of the PN in the catalog of NGC 4594. The dotted curve represents a Gaussian distribution with the same mean as the median of the PNe (1052 km s^{-1}) and a dispersion of 250 km s^{-1} . Compared to the Gaussian, our histogram is somewhat peaky.

A field in the SE was never observed in the candidate-detection phase, so the PNe do not cover the field-of-view evenly. The spatial distribution of the sample is shown in Fig.8.2. The field that was not observed is located in the bottom left. The void in the center shows the limit of detectability of the PNe. We see suggestions of rotation that goes into the page on the left hand side.

To examine the rotation more closely, we split our sample into two bins along the minor axis: objects nearer to the plane of the disk and objects farther away (the cut is made at $67''$). To create the bins, the sample was symmetrized into one quadrant and the velocities were reflected along the major axis around the zero-point of 1024 km s^{-1} (Smith et al. 2000). A comparison of the rotation measured in these bins and integrated-light measurements (Kormendy & Illingworth 1982; van der Marel et al. 1994) appears in Fig. 8.3. Starting with measurements in the plane of the disk and working

Table 8.2 Catalog of PNe in NGC 4594.

ID	RA J2000	Dec J2000	wavelength Å	v_{helio} km s ⁻¹
NGC4594 1001	189.98629	-11.69111	5023.0	954
NGC4594 1002	189.93846	-11.68636	5027.8	1242
NGC4594 1003	189.97792	-11.70503	5023.4	979
NGC4594 1004	189.95063	-11.67158	5023.8	1002
NGC4594 1005	189.97063	-11.68314	5030.5	1407
NGC4594 1006	190.00325	-11.68333	5026.2	1144
NGC4594 1007	189.97129	-11.67161	5027.2	1204
NGC4594 1008	189.96421	-11.65953	5023.6	991
NGC4594 1009	189.99821	-11.68136	5026.6	1168
⋮	⋮	⋮	⋮	⋮
NGC4594 2221	190.11646	-11.58950	5020.9	849
NGC4594 2222	189.98867	-11.58614	5027.2	1227
NGC4594 2223	189.94954	-11.58997	5025.1	1107

NOTES - The positions and IDs are taken from Ford et al. (1996). Velocities are corrected to heliocentric. The full version of the catalog will be available with a publication still in preparation.

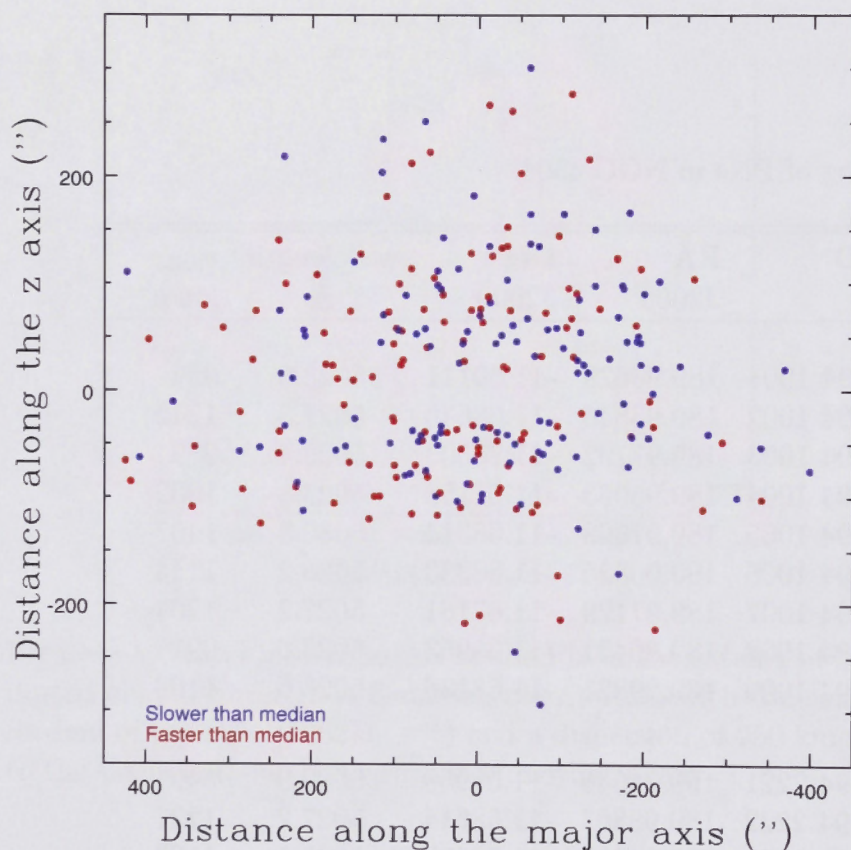


Figure 8.2 Spatial distribution of the PNe in the velocity catalog of NGC 4594. The void in the center shows the limit of detectability— where the galaxy is very bright, we aren't able to see PNe. The empty space in the lower left of this figure shows where one of the fields was not observed in the original detection run (Ford et al. 1996). PNe with velocities higher than the median are show in red and those with slower velocities are in blue. The right-hand side of the galaxy is moving out of the page and the left-hand side is rotating into the page. With a measured major-axis position angle of 88.6° , North is nearly vertical and East is nearly to the left.

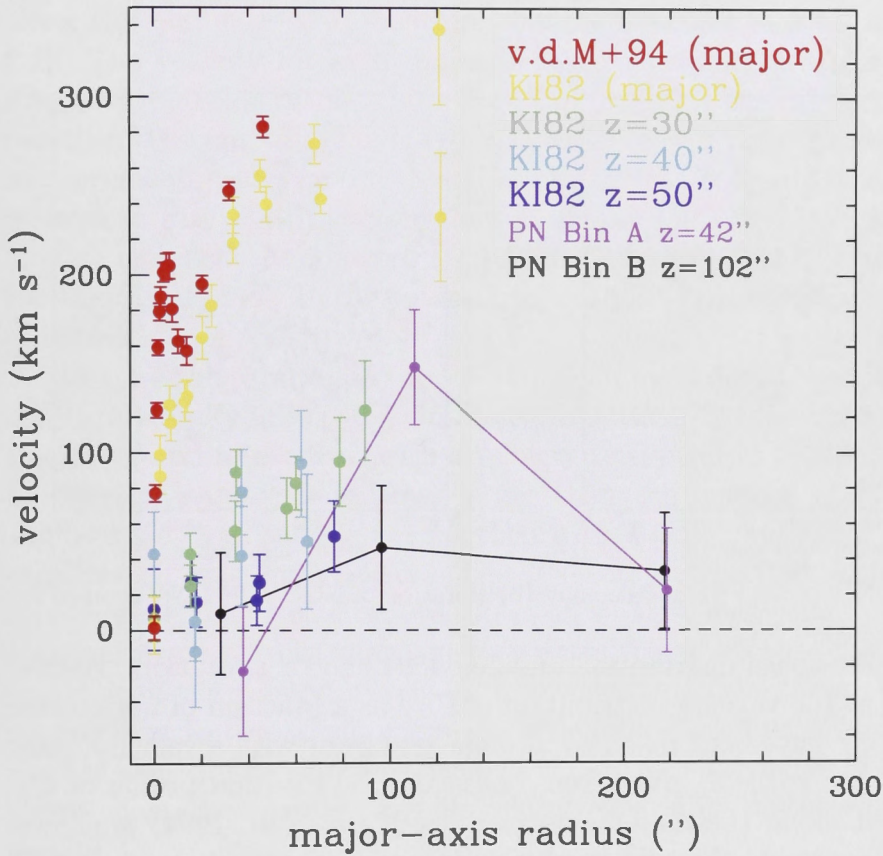
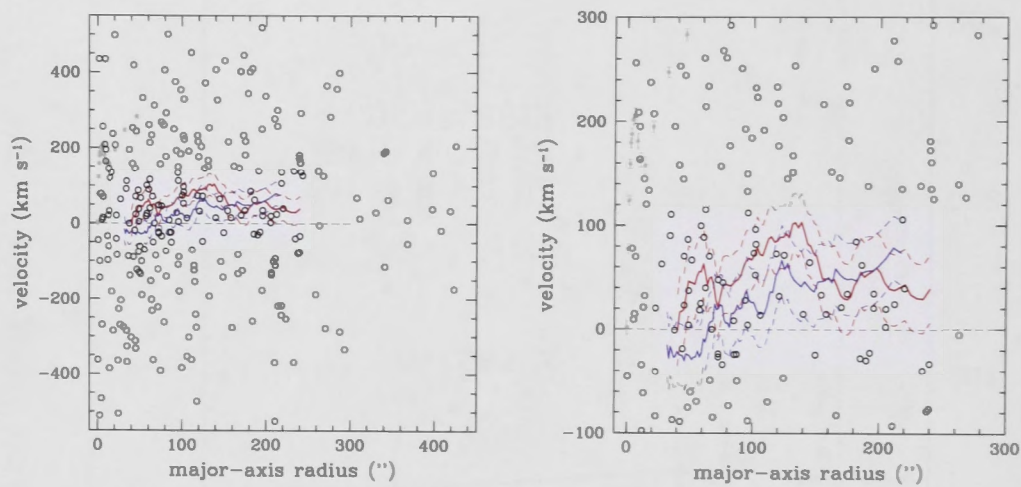


Figure 8.3 Rotation profile of NGC 4594. Following the color-coded key, the amplitude of rotation decreases steadily as one moves away from the plane of the disk. Our most distant measurements come from the PNe (black and magenta). Bin A has a median radius of $42''$. It suggests rotation of as much as 150 km s^{-1} , which is consistent with integrated light measurements from the same area (Kormendy & Illingworth 1982). Bin B ($z=102''$) shows marginal rotation in the same sense that we expect from the light. Both bins show hardly any rotation at the edges—we may be entering a region that is dominated by a non-rotating halo.



(a) Rotation of NGC 4594 PNe, zoomed out (b) Rotation of NGC 4594 PNe, zoomed in

Figure 8.4 Phase-space distribution of NGC 4594 showing rotation. Hollow circles represent the velocity distribution of PNe as a function of major-axis radius. The PNe have been reflected into one quadrant with a velocity zero-point of 1024 km s^{-1} . To give a sense of scale, the rotation profile of the integrated-light along the major axis (van der Marel et al. 1994) is shown in green. In contrast, the planetary nebulae divided into Bins A and B (nearer to the disk and farther from the disk respectively) show more modest velocity offsets from the mean of the galaxy. Bin A is red and Bin B is blue. These values were measured as a running average with 50 objects in each measurement. This result matches the trend shown in Fig. 8.3 of decreased rotation as distance from the plane of the disk increases. It also shows the dropping rotation at large major-axis radii. Fig. (b) shows a zoomed-in version of Fig. (a).

outwards, the rotation becomes progressively less pronounced. By the time we reach the two PN bins (Bin A is objects near the disk and Bin B is objects far away), the rotation is somewhat ambiguous. These measurements indicate that the bulge is rotating, but not cylindrically.

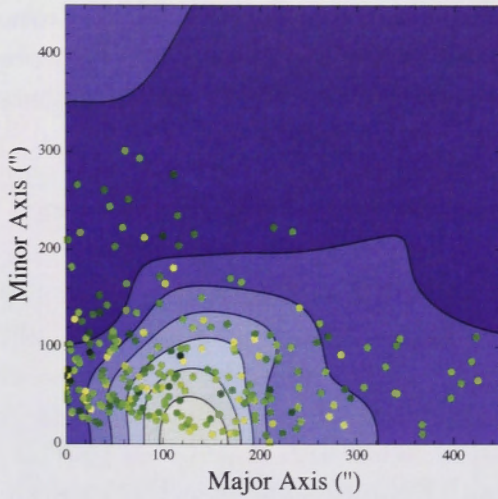
Spatial binning sometimes masks important behavior. To avoid binning along the major axis, we measure running averages in Bins A and B (Fig. 8.4). The velocity for each radius is taken as the mean of 50 objects. We compare the velocity distribution of the total PN sample to the measured rotation. The amplitude of rotation is clearly lower than the integrated-light measurements from van der Marel et al. (1994). Zooming in on the area of interest in Fig. 8.4(b), we see that to almost $150''$ the rotation from Bin A (red) is significantly non-zero ($\sim 100 \text{ km s}^{-1}$), while Bin B (blue) is rotating less rapidly, if at all. In the outer parts, both PN bins show marginal rotation of approximately 50 km s^{-1} .

To show the rotation of the PN sample in more detail, we plot contours of constant velocity in Fig. 8.5. In these plots, the PNe have been reflected over the major and minor axes with a velocity zero-point of 1024 km s^{-1} creating an effective sample four times larger than the number of PN detections. The symmetrized sample is smoothed with a Gaussian kernel to create the contours of constant velocity. The PNe are overplotted with their colors representing their velocities (dark green is slow and yellow is fast). The contours are not constrained in the central parts because the bright bulge and disk of the galaxy prevent us from detecting PNe there. We observe a summit-like feature along the major axis indicating that the rotation curve reaches a maximum¹ and then declines with increasing radius. This maximum occurs at approximately the same major-axis radius as the edge of the disk ($\sim 130''$).

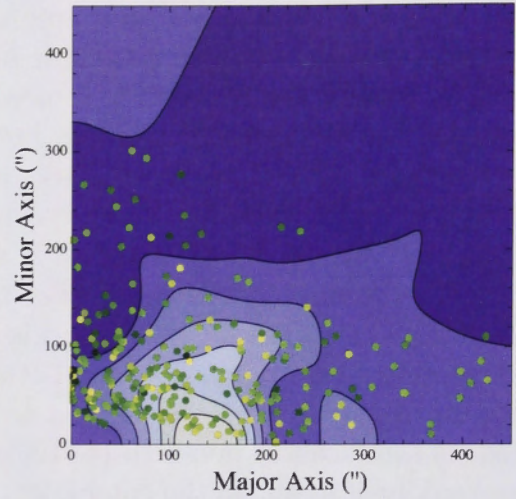
Near the plane of the disk, the contours appear vertical and parallel. This indicates cylindrical rotation and it is observed in boxy bulges which are associated with bars (Kuijken & Merrifield 1995). In contrast, above $z \sim 100''$ the rotation decreases with height and the contours are angled. This implies spheroidal rotation, and it is associated with classical bulges. See the examples from SAURON in Fig. 8.6.

In the case of NGC 4594, the cylindrical behavior near the disk is unexpected for this classical bulge. Detailed information about the velocity fields of early-type galaxies at these radii was unobtainable until recently.

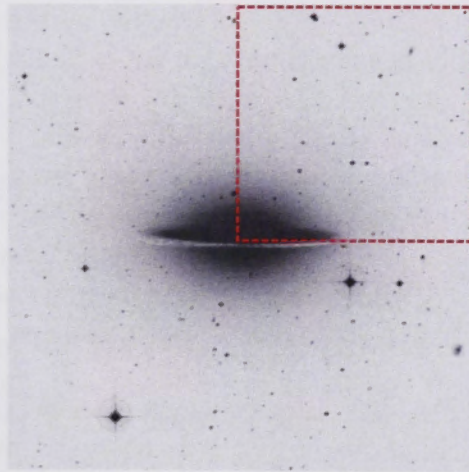
¹Because of the smoothing, the contours are on their own scale and there is no quick translation of the contour levels into velocities measured in km s^{-1} . To estimate the maximum rotation of the PNe, we found the median velocity of the 14 objects located within the fastest contour on the velocity map. We find $V_{\text{max}} = 164 \text{ km s}^{-1}$, which agrees with the binned value in Fig. 8.3.



(a) Velocity contours, 40'' kernel

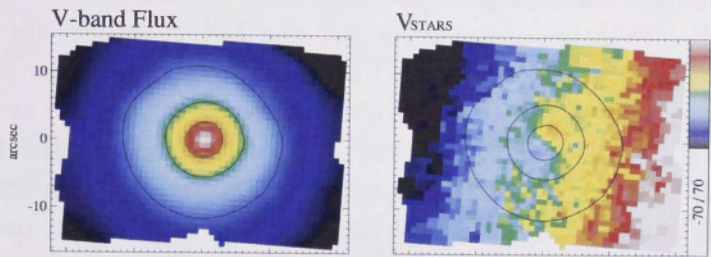


(b) Velocity contours, 30'' kernel

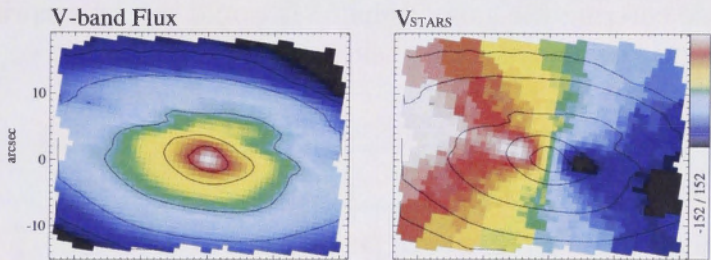


(c) DSS Image of NGC 4594

Figure 8.5 Contours of constant velocity for the PNe in NGC 4594. The PN sample (overplotted) was symmetrized into one quadrant and smoothed with a Gaussian kernel. In (a) the kernel has $\sigma_k=40 \text{ km s}^{-1}$ and in (b) the kernel has $\sigma_k=30 \text{ km s}^{-1}$. Smoothing has the effect of removing the noise, but the general geometry of the rotation remains the same. The color of each PNe indicates its velocity— dark for slow objects and yellow for fast ones. The central part is unconstrained by observations. We observe rising rotation until $\sim 130''$ and then it turns over. (c) shows the DSS image of NGC 4594. The red square marks the region plotted in (a) and (b).



(a) SAURON data for NGC 4698



(b) SAURON data for NGC 5689

Figure 8.6 SAURON data for NGC 4698 and NGC 5689. For each galaxy the isophotes are shown on the left and the velocity map is shown on the right. In (a), NGC 4698 shows the straight velocity contours typical of cylindrical rotation. In (b), NGC 5689 shows spheroidal rotation where a cut parallel to the minor axis would reveal a falling rotation profile. This data covers only the central regions of these Sa galaxies— we are not able to see the turnover in the velocity profile on this scale. These figures are borrowed from Falc3n-Barroso et al. (2006).

Cocato et al. (2009) show the two-dimensional velocity field of NGC 4697, which displays very similar rotation to NGC 4594 in the area that is constrained (see Fig. 8.7). Larger catalogs and a more sophisticated smoothing algorithm could reveal a family resemblance between the dynamics of NGC 4594's bulge and fast-rotating ellipticals.

Combined with other measurements, the PN rotations form a consistent picture. The rotation measured from MMT major-axis long-slit spectra (van der Marel et al. 1994) is still climbing towards 300km s^{-1} at $r_{\text{maj.}} \sim 45''$. This integrated light comes from the disk, which dominates the dynamics. The PNe are not observed near the center, so we wouldn't be probing light from the disk in our measurements² Like the offset long slits from Kormendy & Illingworth (1982), PNe are tracing stars in the bulge. The rotation decreases as distance from the disk increases. The PNe in our most distant (Bin B) show hardly any rotation.

The globular cluster system has the largest spatial extent of all our tracers, and their measurement of zero rotation (Larsen et al. 2002; Bridges et al. 2007) fits in the same story as the integrated light and the PNe. A comparison of the rotation of the GCs to the stars and gas is shown in Fig. 4594GCs. At the limit of our PN detections and in the region covered by the globular clusters, we are entering the galaxy's halo. It would not be surprising to find that the dynamics change as we transition to DM dominance.

8.3 Analysis

8.3.1 Velocity dispersion profiles and mass

The light from the disk of NGC 4594 shows clear rotation on the order of 300km s^{-1} , while the PNe and globular clusters agree that the outer bulge is not rotating as quickly. The disk and the bulge formed through different processes. The disk is luminous and, at such an edge-on inclination, it is easy to measure the kinematics. The bulge, particularly in the outer parts, is harder to study. Using kinematic tracers, we can explore the mass distribution of the outer parts to understand its formation history.

The planetary nebulae were folded along the major axis and split into three equal-number bins. The dispersion was measured assuming a Gaussian distribution. We also applied the robust fitting technique from §5.2.7.2. The effect was not significant because this sample only contains confirmed PN candidates from Ford et al.'s catalog (1996) so we have not plotted the results.

²The PN observations start about $30''$ above the disk. At the distance of NGC 4594, this is $\sim 1.4\text{kpc}$. which is less than the scale height of a typical disk galaxy.

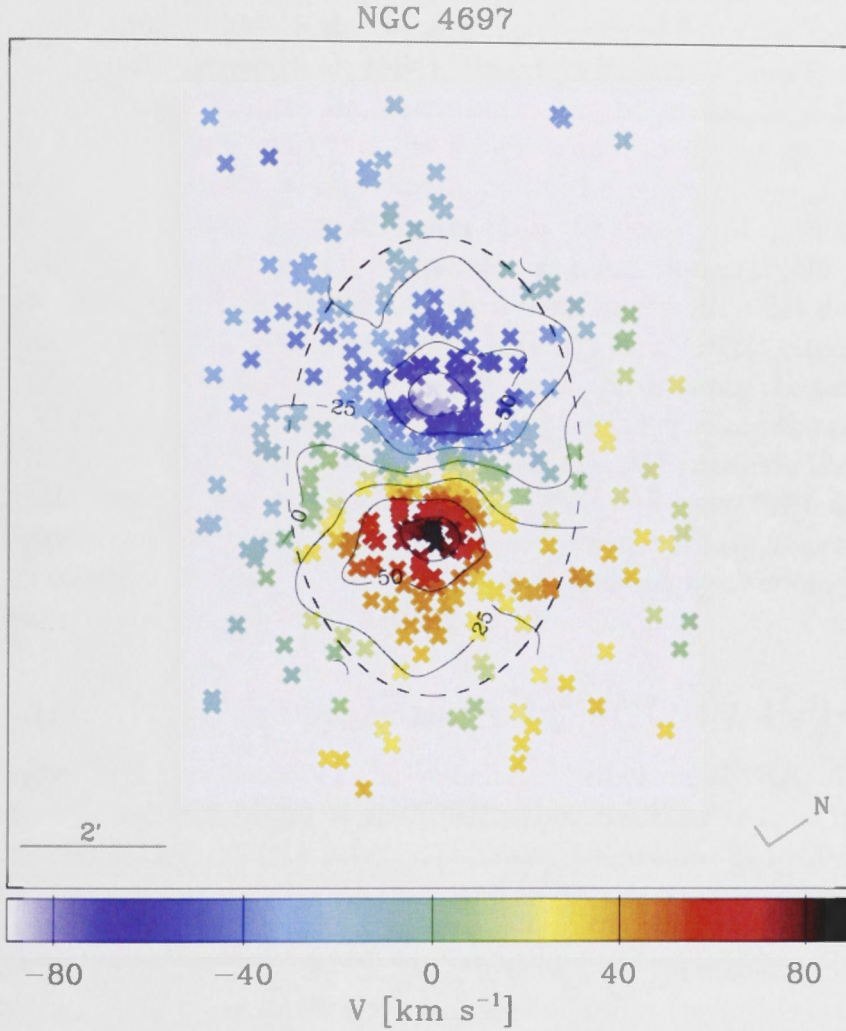


Figure 8.7 Two-dimensional velocity field of NGC 4697. The crosses mark the positions of the PNe and the black lines show contours of constant velocity. The dotted ellipse marks $2R_e$ and the photometric major axis is vertical. Like NGC 4594, these contours are parallel near the equatorial plane and the rotation reaches a maximum around $1 R_e$. This figure is taken from Coccato et al. (2009).

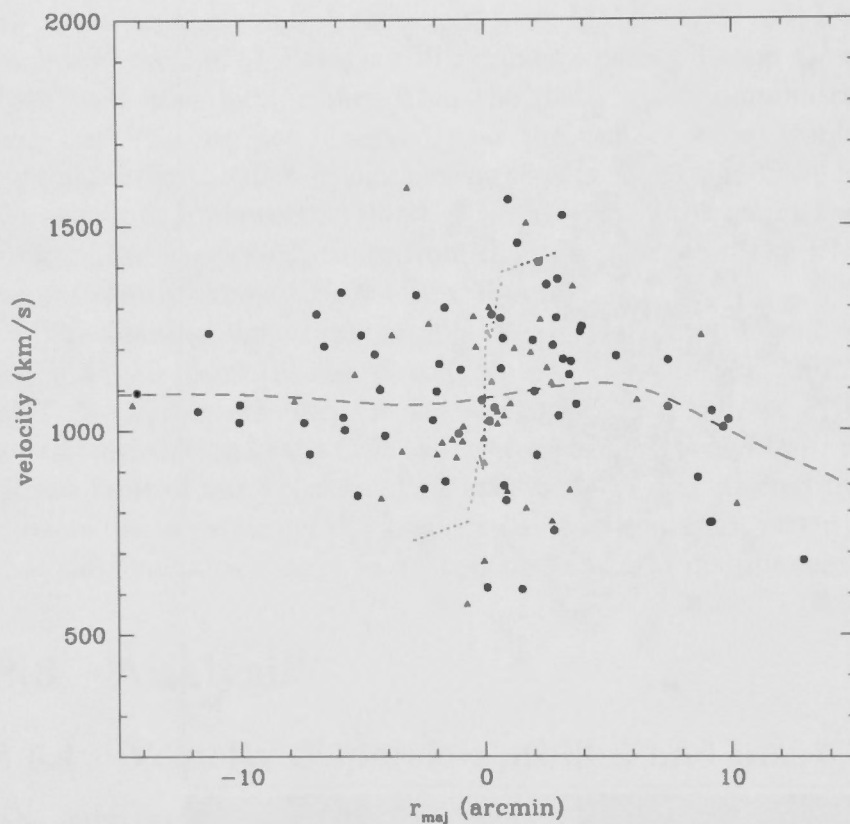


Figure 8.8 Rotation of the the 108 GCs in NGC 4594. This figure is borrowed from Bridges et al. (2007). The blue GCs are shown with circles and the red GCs are shown with triangles. The dashed line is a smoothed fit to the GC velocities, and the dotted line shows the stellar and gas rotation curve of the disk from van der Marel et al. (1994) and Kormendy & Westpfahl (1989). Like the PNe, the GCs show negligible rotation compared to the disk.

Fig. 8.9 shows the dispersion profile of the galaxy as a function of major-axis radius. The planetary nebula dispersions extend out directly from the integrated-light measurements taken in a similar area (Kormendy & Illingworth 1982). The two tracers imply a flat profile with $\sigma \approx 230 \text{ km s}^{-1}$. This profile contrasts sharply with the dispersions measured from the stellar light in the disk (van der Marel et al. 1994). Based on Fig. 8.10 from Ford et al. (1996), we expect the PNe to be consistent with the stellar light from the bulge, but a comparison with the disk's light would look very different. Although neither component is very luminous at the edges of our observations, the density of the disk drops off faster than the density of the halo.

In Fig. 8.11 we measure dispersion as a function of height above the disk. Like the major axis, the minor axis is consistent with a flat dispersion profile with $\sigma \approx 230 \text{ km s}^{-1}$. Kormendy & Illingworth (1982) cite a dispersion of 210 km s^{-1} in the bulge. This plot helps us to constrain the total mass profile of NGC 4594. The mass is not dropping off faster along the projected minor axis than it is along the projected major axis. We conclude that, to the limits of our observations, the mass of the bulge is consistent with a near-spherical distribution. Also, the dispersion measurements are significantly larger than the rotation velocity, so the system is supported by random motions in the area covered by the PNe. See Fig. 8.12.

8.3.2 How the stars move in NGC 4594's bulge

Higher-order moments of the velocity distribution of NGC 4594 were measured by van der Marel et al. (1994). Their data covers light from the disk of the galaxy. We are interested in exploring these same quantities for the bulge and halo of this galaxy. As discussed in §1.3.2, we don't have the statistical signal-to-noise necessary to measure higher-order parameters of the PN velocity distribution like h_3 and h_4 . However, we can measure the rotation and we can make more qualitative statements about the orbital structure.

As discussed above, the central part of the galaxy is strongly influenced by the dynamics of the disk, but the integrated light, the globular clusters and the PNe agree that the outer parts are rotating much more slowly. The difference in rotation underlines the histories of the two components. Bulges and halos are built up through mergers, some of them disruptive. Random motions dominate the ordered motion of rotation. Disks like the ones seen in S0s and possibly this disk are thought to be created by gas settling later. Because this disk is intact, we assume that it formed after the epoch of major merging. The disk represents about 10% of the light in NGC 4594 (Burkhead 1986) so we can conclude that the galaxies that merged together before the disk formed were not gas rich (similar to the Milky Way today) or that a lot

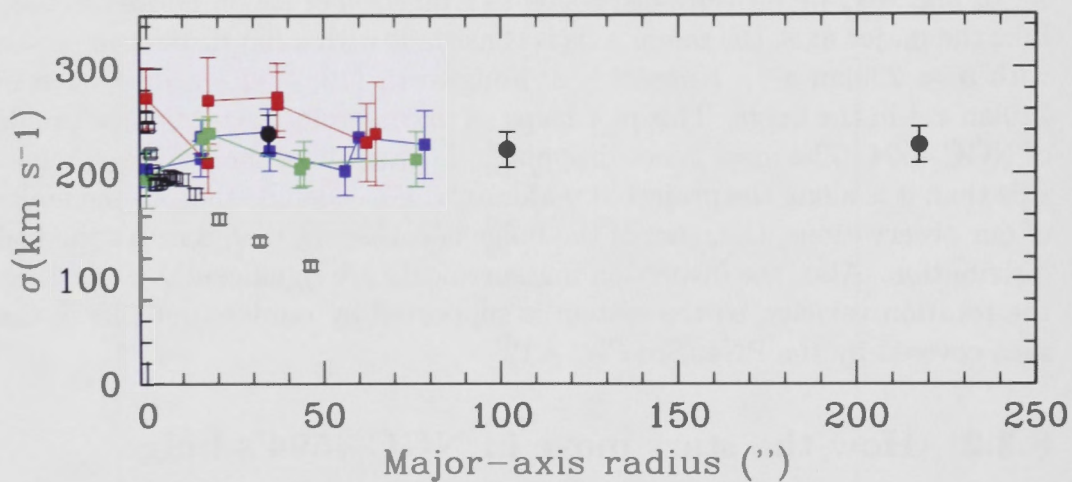


Figure 8.9 Velocity dispersion profile of NGC 4594. The black circles show the planetary nebula dispersions. The colorful squares show integrated-light measurements by Kormendy & Illingworth (1982) from slits that are parallel to but offset from the major axis by 30″ (blue), 40″ (red) and 50″ (green). At smaller radii, the hollow squares show the dispersion measured from integrated light along the major axis (van der Marel et al. 1994)— the marked drop in dispersion shows that the mass of the disk is dropping off much faster than the bulge around it.

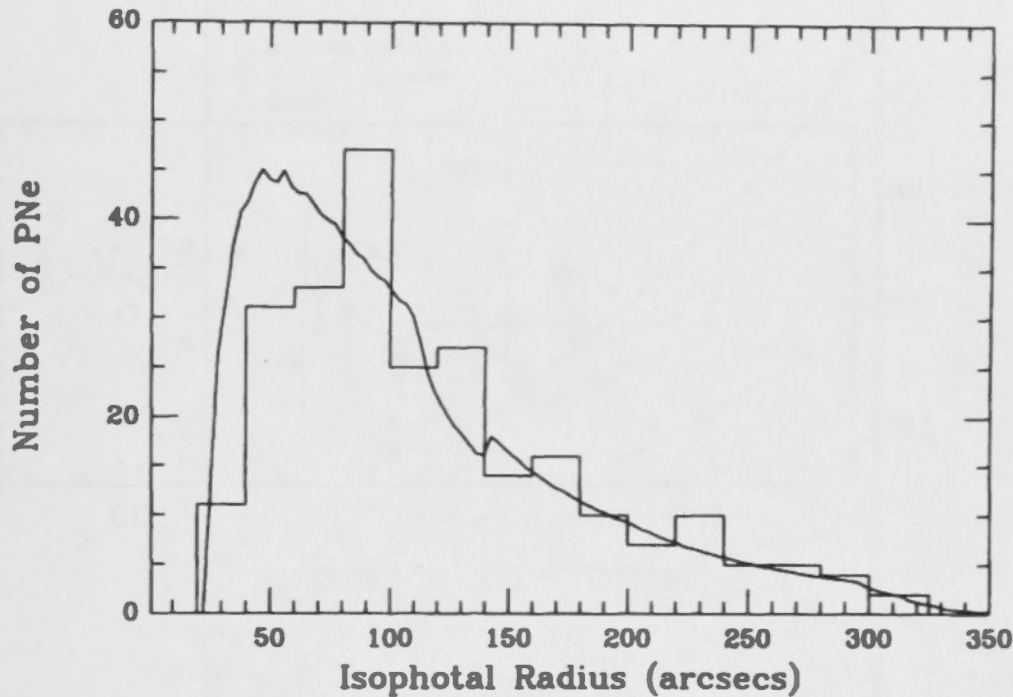


Figure 8.10 Comparison of the radial distribution of PNe to the light. The histogram represents the number of PNe at each radius from the original catalog (Ford et al. 1996). The line represents the light measured in the observed fields. The excellent match implies that they are consistent tracers and we can combine them for measurements of the dispersion profile (for example). The disagreement at small radii illustrates the limit of detectability also seen in Fig. 8.2. This figure is copied from Ford et al. (1996).

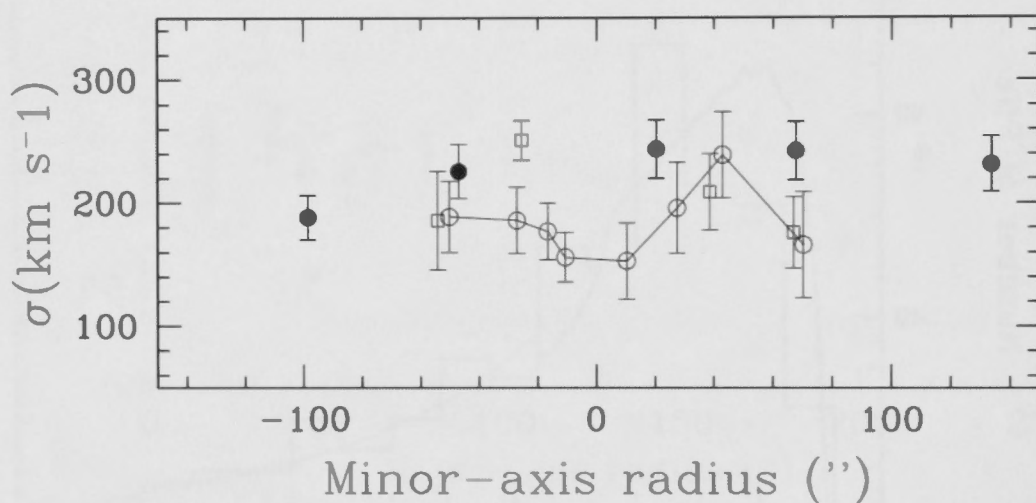


Figure 8.11 Minor-axis velocity dispersion profile of NGC 4594. The black circles show the dispersion of bins of PNe as a function of height above the equatorial plane. They suggest a fairly flat dispersion profile, possibly falling in the outer parts. The hollow points are taken from integrated-light spectra (Kormendy & Illingworth 1982) with the squares representing measurements along the minor axis and the circles showing a slit that is displaced by $50''$. Some integrated light points from the center have been removed because they included light from the disk.

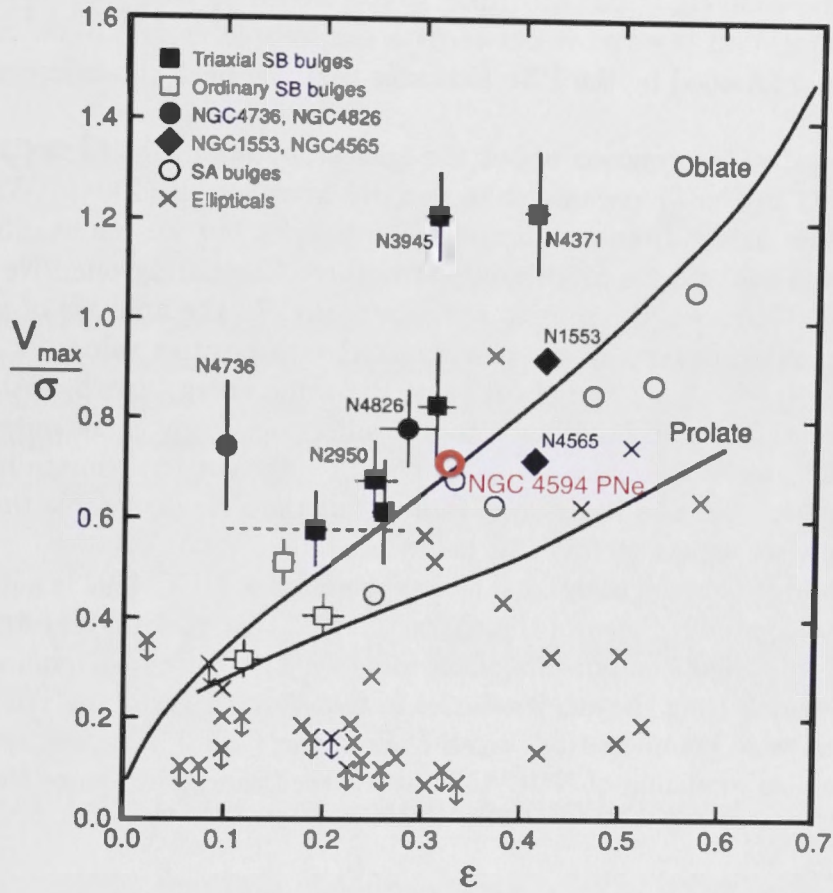


Figure 8.12 Comparison of V/σ ratio to ellipticity for a range of ellipsoidal stellar systems. ϵ is defined as $1 - \text{apparent axial ratio}$. The bulge of NGC 4594 ($V_{\text{rot}}=164 \text{ km s}^{-1}$, $\sigma_{\text{max}}=230 \text{ km s}^{-1}$, $\epsilon=0.32$) is overplotted in red towards the bottom of the plot in the area dominated by dispersion-supported systems. Other galaxies similar to NGC 4594 are shown with black hollow circles. This plot is taken from Kormendy & Kennicutt (2004).

of the gas was used up before the disk settled.

Since hierarchical merging is expected to transfer angular momentum outwards in bulges and ellipticals (Quinn & Zurek 1988), Bridges et al. (2007) suggest that the mergers transferred this rotation even farther out into the halo than the area probed by the globular clusters. Our PNe cover more than four effective radii ($R_e=102''$ according to Kormendy & Westpfahl 1989), but we see less rotation as we move outwards in our sample. The two-dimensional velocity field afforded by the PNe indicates that the peak rotation occurs at $\sim 1.3R_e$.

Quantitative information about the anisotropy of the disk's stellar light is embodied in the h_4 parameter in van der Marel et al. (1994). We can't extract those details from our discrete distribution, but we can examine the histogram in Fig. 8.1 for more subtle structure. Comparing our PNe to the overplotted Gaussian, the sample appears peaky. In the analysis of absorption line profiles, peaky shapes are associated with positive values for h_4 and radial anisotropy. Since radial orbits of the same energy reach farther out than tangential ones, it is common to see radial anisotropy in the outer parts of ellipsoids (see §7.3). Our sample size is not sufficient to estimate how the anisotropy changes as a function of radius, but the PNe do sample the outer parts where we expect to find this behavior.

As a bridge between early- and late-type galaxies, NGC 4594 is a interesting system to study. Some of the characteristics that make it so interesting (the disk+ellipsoid components, axisymmetry, the rotation) require more complex models than the other galaxies in this sample. Semi-analytic, rotating models were completed by Jarvis & Freeman (1985). We will return to the dynamical modeling of NGC 4594 at a later time with a more elaborate approach.

Chapter 9

Conclusions

In this section we assess what we have learned about each of the galaxies in our sample and what can be inferred about early-type systems in general. The results in the text are reiterated here to create a summary of this work's contribution. We conclude by revisiting the goals presented the introduction and evaluating our progress.

9.1 What the planetary nebulae say about the kinematics

9.1.1 NGC 1399: Slow-rotating archetype

We measured the velocities of 146 planetary nebulae (PNe) in NGC 1399, 132 of which had never been done before. We find marginal rotation in the PN sample ($\sim 20\text{km s}^{-1}$) with an offset kinematic major axis and kinematic twist in the outer parts. This result places NGC 1399 in the slow-rotating population of early-type galaxies (ETGs) described in Table 1.1. This galaxy is a giant elliptical and the dominant object in its cluster. The rotation confirms that this kind of galaxy falls into the boxy-bulged, slow-rotating part of the ETG dichotomy.

The PNe in our sample show a much flatter dispersion profile than previously thought (Arnaboldi et al. 1994b), which agrees well with measurements from integrated light and the decontaminated red globular cluster sample (Schuberth et al. 2010). This galaxy shows no signs of truncation or a transition to the halo potential at the radii we are examining.

9.1.2 NGC 3923: Unexpected rotation

We identify 108 PNe in NGC 3923 and measure their line-of-sight velocities. The sample is combined with new long-slit spectroscopy of the galaxy. In the inner parts, our measurements resemble previous observations (Carter et al. 1998). In the radial range that had not been measured before, we see a change in the behavior. The integrated light implies that, outside $50''$, the galaxy is rotating along the major axis and the orbits become more tangential. This finding supports angular momentum transfer due to a merger (Quinn & Zurek 1988).

The rotation result is surprising because the highly coherent and regular nature of the shells argues for a restrictive merger geometry. Models (Dupraz & Combes 1985; Quinn & Hernquist 1987; Hernquist & Quinn 1989) imply that NGC 3923 must have formed in an on-axis interaction. The measured rotation implies that the shell-formation merger need not have been as aligned as we might assume. Our observations are consistent with either an edge-on, rotating oblate galaxy or a prolate or triaxial galaxy tumbling along the line-of-sight and with the rotation axis in the plane of the sky. Any tumbling would need to be on a timescale slower than the oscillations of the shell material in order to preserve the defined appearance. Since these the integrated light observations were taken along the positive major axis, corresponding data from the negative major axis would be extremely helpful for understanding the rotation, mass and anisotropy of the outer parts. Kinematic data on the outer parts from PNe and integrated light open new possibilities for shell formation.

9.1.3 NGC 1316: Largest sample supports consistency of PNe and stellar light

We measure the velocities of 796 PNe in NGC 1316.¹ Additionally, we find 69 PNe that belong to the nearby galaxy NGC 1317. The NGC 1316 sample has a total rotation of $85 \pm 11 \text{ km s}^{-1}$ at P.A. $64 \pm 9^\circ$, which agrees with the photometric major axis. The kinematic major axis has a constant P.A. except for one measurement that we suspect is affected by PNe from NGC 1317. The rising rotation profile could either corroborate our contamination suspicions or indicate a transfer of angular momentum outwards (Quinn & Zurek 1988).

This extensive sample provides another example of the PN number density tracing the distribution of the stellar light in early-type galaxies (see Coccato et al. 2009). This confirmation is extremely valuable going into

¹NGC 1316 has the largest sample outside the local group known to me. See Merrett et al. (2006) for an enormous sample of PNe in M31.

dynamical modeling since our models begin from the premise that PNe and stars provide consistent tracers of the kinematics at all radii.

The v_{rms} profile of NGC 1316 drops off faster than the dispersion profiles of the other galaxies in our sample. The measurements interface seamlessly with integrated-light data from Bedregal et al. (2006) at $\sim 150''$. Such consistent kinematics further support our claim that the PNe are tracing the same population as the stellar light.

9.1.4 NGC 4594: Rotation of a bulge with an embedded disk

This sample includes 266 PN velocities observed as a follow-up to the catalog published by Ford et al. (1996). The PNe are tracing the kinematics of the bulge component to add to already substantial measurements of the disk kinematics. We measure rotation in the PNe in the same sense as the rotation of the disk. When the sample is divided by height above the disk, it is clear that the amplitude of rotation decreases with distance from the plane of the disk. This implies that the bulge is rotating spheroidally. However, the contours of constant velocity indicate that the rotation near the plane of the disk is more cylindrical. The PNe at large major-axis radii show a drop in rotation— we could be reaching the limit of the area affected by the disk’s rotation.

The flat dispersion profile of the PNe contrasts sharply with the disk’s dispersion profile. This is an indication that the mass of the bulge drops off much more slowly than the mass of the disk. To the limits of our observations, the dispersion profiles along the major and minor axes appear the same, which implies that the bulge’s mass is nearly spherical at these radii.

For the PN sample, the maximum dispersion is $\sim 230 \text{ km s}^{-1}$ and the maximum rotation is 164 km s^{-1} . Comparing its V_{rot}/σ_{max} to the ellipticity (0.32 from Jarvis & Freeman (1985)), the bulge of NGC 4594 lands in at the upper edge of the area occupied by Sa bulges. For the PNe, rotation is still important in the dynamics of the bulge.

9.2 What the models say about the galaxies

9.2.1 NGC1399: Implied triaxiality

We used photometry, integrated-light kinematics, and a combined (planetary nebula and globular cluster) discrete tracer distribution to constrain axisymmetric NMAGIC models of NGC 1399. Notably, the integrated-light

kinematics favored a smaller mass than suggested by the discrete tracers or theoretical predictions (Gerhard 1993). A more concentrated DM halo would improve the agreement between integrated light and PNe, but the preferred solution is a triaxial distribution. Triaxial systems have more flexibility in their anisotropy, which may allow a model that fits both kinematic tracers. Further indicators of triaxiality include the gradient in the kinematics measured by the parallel-to-minor-axis long slit (Saglia et al. 2000) and the offset between the kinematic and photometric major axes. The evidence for triaxiality in NGC1399 is not surprising because the slow-rotating population of ETGs is associated with triaxial distributions.

Our models allow us to compare NGC 1399 to predictions for the dark and luminous mass contents. Our model has a mass-to-light ratio of $9.8 < \Gamma_B < 10.1 M_\odot/L_\odot$ which falls within the uncertainty of predictions from dynamical models in Saglia et al. (2000) and single-burst stellar population models in Napolitano et al. (2005). The NMAGIC models of NGC 1399 yield dark-matter mass fractions of 5-15% within $1 R_e$. At $5 R_e$, 55-75% of our model is composed of dark matter. These estimates agree with predictions in the literature (Gerhard et al. 2001; Cappellari et al. 2006; Thomas et al. 2007).

9.2.2 NGC 3923: Rotating galaxy with a lower dark-matter mass fraction

We fit integrated-light and planetary-nebula dispersions for NGC 3923 with a non-rotating, spherical Jeans model. The model assumes constant anisotropy, a constant mass-to-light ratio and a pseudo-isothermal DM component. We find a mass-to-light ratio of $12 M_\odot/L_\odot$ which is towards the upper limit of values measured for other galaxies (Napolitano et al. 2005; Binney & Tremaine 2008). Our model is slightly radially anisotropic ($\beta_0 = 0.175$) which is consistent with the integrated-light measurements from the inner parts. The integrated-light measurements indicate that constant anisotropy is probably not a very good assumption for this galaxy. The model's anisotropy is more consistent with the integrated light measurements from small radii than large radii, which is not surprising since anisotropy is easier to fit in the regions dominated by stellar light.

We find a core radius for our dark matter distribution of 12.25kpc which sits in the range predicted by Hernquist & Quinn (1987) (8.7-17.3kpc). σ_{DM} is 375 km s^{-1} . At $1 R_e$, our model is 7% dark matter and predictions in the literature span 5-50% (Gerhard et al. 2001; Cappellari et al. 2006; Gavazzi et al. 2007; Thomas et al. 2007; Das et al. 2010). At $5 R_e$, our mod-

els are 58% dark matter which is low compared to other galaxies and models (see references for 1 R_e and results for NGC 1399). By the time we reach the limit of our observation constraints, our model of NGC 3923 is 78% dark matter. Our estimates are slightly lower than expected which supports the speculation from Cappellari et al. (2006) that the fast-rotating population of ETGs have $\sim 30\%$ less dark matter. The model ties together our observations and previous discussions on the mass content of early-type galaxies.

9.2.3 NGC 1316: Supporting evidence for estimates of dark matter content

Like NGC 3923, NGC 1316 was fit with a non-rotating spherical Jeans model. In this case, we fit integrated-light dispersions from Bedregal et al. (2006) and v_{rms} measured from the planetary nebulae. We considered a self-consistent model with constant anisotropy and mass-to-light ratio. The difference between the kinematics of the observations and the model in the outer parts underscores the importance of dark matter. Our final model included a pseudo-isothermal dark matter distribution with $\sigma_{DM}=255\text{km s}^{-1}$ and a core radius of 10kpc. The stellar component has a mass-to-light ratio of 3.1 and radial anisotropy ($\beta_0=0.525$). This model does not allow for the anisotropy to change with radius, but our result fits the observations in the inner parts and our expectations of radial orbits in the outer parts.

At 1 R_e , $\sim 31\%$ of the model's mass is dark matter. This value is in very good agreement with estimates from stellar population models (Cappellari et al. 2006), from strong and weak lensing (Gavazzi et al. 2007; Barnabè et al. 2009) and from dynamical models (Gerhard et al. 2001; Thomas et al. 2007). At 5 R_e , the fraction has increased to 76%. At 100 kpc, where the observational constraints end, our model is flattening to $\sim 85\%$ dark matter, which agrees with estimates from X-ray gas (Das et al. 2010).

9.3 What these examples say about early-type galaxies in general

We now revisit the questions posed in the Introduction. In the context of NGC 1399 and other cD galaxies, what is the shape of a halo that is comprised of many cannibalized galaxies? Observations and NMAGIC models agree that NGC 1399 is best described as a triaxial distribution. This places evolved systems like cD galaxies into the slow-rotating, triaxial portion of the ETG dichotomy. We expect many generations of hierarchical merging to result in

a dispersion-supported, triaxial system.

Focusing on the 10% of ellipticals that display shell-like structures (Priour 1990), we hoped to use the PN kinematics to learn about shells and the merger events that made them. The PN sample of NGC 3923 does not have enough objects to study specific attributes of the shells. The rotation measured in both the integrated light and the PNe demands a re-evaluation of our understanding of shell formation. We assumed that a set of organized and aligned shells could only result from a nearly on-axis merger (Hernquist & Quinn 1989), but rotation in the outer parts allows for a broader definition of possible formation scenarios. One possible scenario is that the central galaxy is a nearly-axisymmetric oblate rotator with the shell material following a tight $E-L_z$ relation, but not necessarily one with $L_z=0$. Another possibility is a prolate or triaxial galaxy tumbling slowly along the line-of sight. The new kinematics belie our understanding of shells as delicate structures that form in highly restricted circumstances. They open up new possibilities for learning about shell formation.

NGC 1316 represents the brightest galaxy in its cluster, and it is evidently a merger remnant. Similarities with cDs like NGC 1399 are implied, but the kinematics indicate very different dynamics. NGC 1316 is rotationally flattened with aligned kinematic and photometric major axes. The rotation is rising in the outer parts which could represent the outward transfer of angular momentum due to the merger Quinn & Zurek (1988). It is an S0(pec) galaxy, and it might be better classified as a proto-NGC 4594 than a proto-NGC 1399. We already see rotation, a large bulge and indications that there is a gas left over to form a disk later. It belongs in the fast-rotating, oblate section of the early-type dichotomy. We infer that it would need to undergo several more major mergers to gain the more dispersion-dominated, triaxial attributes of a NGC 1399-like system, but it may be a juvenile Sombrero-like system.

We are still exploring the relationship between elliptical and disk galaxies. Examples like S0 and Sa galaxies represent a bridge between the classes. In the case of NGC 4594, the bulge's characteristics change with radius. Tracers like PNe and globular clusters probe the outer parts where the bulge shows negligible rotation. Measured closer to the disk, Sa galaxies look like fast-rotating disk objects. This work shows that the relationship between the galaxy classes is highly dependent on the scale of the observations.

Gerhard et al. (2001) predicted that the transition to dark matter dominance occurs between 2-4 R_e . NMAGIC models of NGC 1399 indicate that the crossover happens around 2.2 R_e for models favored by the integrated light. For the model favored by the discrete tracers, the dark matter mass profile is shallower, and the dark and luminous components are equal at ~ 4.4

R_e . Jeans modeling of NGC 3923 results in a transition point at $4.0 R_e$. NGC 1316's Jeans model has a luminous to dark crossover at $1.8 R_e$. The galaxies in our sample form a consistent picture with the 21 objects addressed by Gerhard et al. (2001).

Cappellari et al. (2006) suggested that fast rotators may have $\sim 30\%$ less dark matter. Our results are ambivalent. N3923 supports the idea. Jeans models show that the amount of dark matter necessary to match the observed kinematics in NGC 3923 is less (indeed $\sim 30\%$ less) than predictions made from stellar population models, lensing and dynamical modeling (Gerhard et al. 2001; Cappellari et al. 2006; Gavazzi et al. 2007; Thomas et al. 2007; Das et al. 2010). However, N1316, with a much larger sample and a clearer rotation signal, does not show a deficiency in dark matter compared to the predictions. The dark-matter mass fraction of NGC 1316 is in excellent agreement with predictions from lensing and modeling. The inconsistency in our results may be due to a degeneracy in the mass-to-light ratio and DM parameters of the models. Results from ATLAS^{3D} and other projects should provide useful information on the connection between the galaxy assembly history and the dark matter halo structure.

Chapter 10

Future Work

10.1 New areas to be explored

The rotation measured in the outer parts of NGC 3923 could represent the beginning of a renewed inquiry into the formation of shells around early-type galaxies. Previous observations did not cover the outer parts of the shell systems. NGC 3923 was thought to be a straightforward and highly regular system of shells, but the behavior of the PN and integrated light kinematics makes less restrictive formation scenarios more appealing even for this object. Similar observations of other shell galaxies could provide valuable insights into how these objects form.

The velocity map of NGC 4594 indicates that the bulge does not follow the expected spheroidal rotation of a classical bulge. As radially-extensive, two-dimensional velocity fields become available for more galaxies, it will be possible to explore the dynamics of fast-rotating ETGs. We can explore the connection between the observed rotation and possible formation mechanisms.

10.2 Expanding the sample and further exploring these objects

Observations of planetary nebulae are detection limited. Deeper observations will open up the more populous, faint end of the planetary nebula luminosity function. Our analysis of discrete tracers is limited by the effects of spatial binning and undersampled distributions. NGC 3923 is a good candidate for additional observations. More tracers would allow us to examine the kinematics of the detailed structure in the shell system. The next generation

of larger telescopes will go deeper making larger catalogs available for nearby galaxies and making PN samples for more distant systems attainable.

Since number density, not brightness, follows the galaxy's light distribution, we should be able to detect PNe at very large radii. Expanding our sample not only in depth, but also spatial extent would provide information about the halos and, assuming the detection of intracluster PNe, the limit at which these tracers are no longer bound.

A more comprehensive survey of PNe in nearby galaxies is being undertaken by the Planetary Nebula Spectrograph (PN.S) team (Douglas et al. 2002). This project has already provided useful constraints on dark matter content in early type galaxies (Romanowsky et al. 2003; de Lorenzi et al. 2009) and the consistency of PNe and stars as kinematic tracers (Coccato et al. 2009). We can expect interesting results as their sample of galaxies increases.

10.3 Incorporating globular cluster kinematics into the models

The compatibility of globular cluster (GC) and planetary nebula (PN) kinematics has been shown for some galaxies (Brodie & Strader 2006; Schuberth et al. 2010). Including velocities from the red GCs is another way to expand the number of objects in our discrete tracer catalogs and the number of galaxies for which we have catalogs. Since early-type galaxies usually contain many more detectable GCs than PNe, globular clusters promise valuable kinematic constraints on the outer parts.

The work on the NGC 1399 planetary nebula catalog was concurrent with the globular cluster work in Schuberth et al. (2010). In the end, we were able to compare the two tracers and they were remarkably consistent. This agreement may be present in many other early-type galaxies and should be checked. Combining catalogs of PNe and GCs as we have done for NGC 1399 to constrain the outer parts of dynamical models could be important for understanding the under-observed edges of early-type systems.

In addition to the recent work by Bridges et al. (2007), new globular cluster observations of NGC 4594 would provide a much-needed increase in sample size. Since GCs are the most radially distant kinematic tracer, they hold the key to measuring evidence of the outward transfer of angular momentum (Quinn & Zurek 1988). In this and other systems, GCs are the only tracer with the spatial range to explore the relative importance of rotation and random motion in the halos.

10.4 Advancements in modeling techniques

As our observations improve, so does our appreciation of the complexities and idiosyncrasies of early-type galaxies. In contrast, our models move forward under dubious simplifying assumptions. The analysis in this work would be improved by the introduction of rotating models in the case of NGC 1316 and NGC 3923. Models of these galaxies also relied on assumptions of constant mass-to-light ratios and constant anisotropy. Particularly in the case of anisotropy, our observations emphasize the error in this assumption. The Jeans modeling has scope for improvement and development.

A dynamical model of NGC 4594 was outside the scope of this thesis, but it needs to be done. The system is clearly axisymmetric and, with constraints on the orientation from the inclination of the disk, we have an uncommonly good picture of the physical situation.

The axisymmetric NMAGIC model of NGC 1399 represents the second stage of the modeling process. The system was not well described by the spherical model in stage one. Our results imply that NGC 1399 is better understood as a triaxial galaxy, so more complex models join the list of tasks for the future.

NMAGIC models represent an improvement over the Jeans modeling in this thesis because, in principle, it is not necessary to make a priori assumptions about the luminous potential. The current barrier to more extensive NMAGIC modeling is that the process is time intensive. There is also room for improvement in the functionality of NMAGIC. In particular, fitting individual line-of-sight velocities for the discrete tracers using an integrated robust-fitting technique would preserve some information on the velocity distribution that is lost in the current binning approach. As the NMAGIC code evolves, it will become more user-friendly, more efficient with the discrete observations and more pervasive.

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