Bars in Edge-On Spiral Galaxies

by

Martin Bureau

A thesis submitted for the degree of

Doctor of Philosophy

of The Australian National University

Mount Stromlo and Siding Spring Observatories
Institute of Advanced Studies
The Australian National University

August 1998

To my mother, who nurtured my curiosity toward nature.

Declaration of Authorship

I hereby declare that the work presented in this thesis is that of the candidate alone, except where indicated in the text and as described below.

The following chapters are modified versions of papers submitted or shortly to be submitted for publication.

Chapter 2 *The Shape and Figure Rotation of NGC 2915's Dark Halo*, by Bureau, M., Freeman, K. C., Pfitzner, D. W., & Meurer, G. R. (submitted to The Astronomical Journal)

Chapter 3 *Bar Diagnostics in Edge-On Spiral Galaxies. I. The Periodic Orbits Approach*, by Bureau, M., & Athanassoula, E.

Chapter 4 *Bar Diagnostics in Edge-On Spiral Galaxies. II. Hydrodynamical Simulations*, by Athanassoula, E., & Bureau, M.

Chapter 5 *The Nature of Boxy/Peanut-Shaped Bulges in Spiral Galaxies*, by Bureau, M., & Freeman, K. C. (to be submitted to The Astronomical Journal)

The candidate wrote the above papers and co-authors contributed to refining the text.

In Chapter 2, D. W. Pfitzner contributed preliminary results from a set of CDM simulations. E. Athanassoula provided a number of routines used in Chapters 3 and 4.

Martin Bureau

August 1998

Acknowledgements

The research presented in this thesis would not have been possible without the cooperation, advice, and support of many people, to whom I am indebted.

First, I am indebted to Ken Freeman, for accepting to supervise me in the path I chose, for providing valuable advice and insightful comments throughout my thesis, and for sharing his knowledge and providing much appreciated guidance. Thank you for treating me as an equal, for teaching me to identify the important questions and to be open to new ways of answering them, and thank you mostly for sharing with me the excitement of research. I hope this is only the beginning of a long association. I also wish to thank Agris Kalnajs, for many lengthy discussions and for his tremendous knowledge and critical views of various works. I am grateful to Lia Athanassoula and Albert Bosma, for welcoming me in their group at the Observatoire de Marseille, and wish to thank Lia for a fruitful collaboration and for giving me access to her hydrodynamical models. Merci aussi à Jean-Charles et Eric pour le support informatique. Similarly, I am grateful to Gerhardt Meurer for access to the NGC 2915 data.

I am also indebted to Jeremy Mould and Lister Staveley-Smith, for getting me involved in various side projects during my thesis. Je ne saurais comment remercier Claude Carignan, à l'Université de Montréal, pour avoir initié mon intérêt pour la dynamique des galaxies, et pour avoir, par la suite, suggeré et supporté ma venue à Mount Stromlo.

Thanks also to Tim de Zeeuw, Ortwin Gerhard, Daniel Pfenniger, and their respective institutes, for allowing me to visit, to exchange ideas, and mostly for advice at a crucial stage of my thesis. A big thank you also to Linda Sparke, for getting me started on the periodic orbits project. I extend similar thanks to the many people who provided comments on my work in a hallway, sipping a cup of coffee, or over a meal, during conferences. These include Ron Buta, Françoise Combes, Jerry Sellwood, and many others.

Finally, I want to express my sincere gratitude to the staff of Siding Spring Observatory, the Australia Telescope National Facility, and the workshops here at Mount Stromlo, for providing and maintaining top quality instruments. I am equally grateful to the administrative, computing, and other support staff at Mount Stromlo Observatory, without whom none of this work would have been possible. A thousand thanks as well to the academic staff, who were always available when needed.

Of course, a great deal of personal and social support is also required to undertake such large task as a thesis, and I am indebted to many people, friends and family.

Tout d'abord, j'aimerais remercier ma mère, à qui cette thèse est dédiée. Son support et ses encouragements, depuis le début des mes études, sont à l'origine de mes succès. Merci aussi pour m'avoir donné le pouls de Montréal pendant mon absence. Merci également à mon père, pour son amour de la nature, qui m'a inspirée. I must of course thank the other students of Mount Stromlo, who have made my stay a memorable experience. A special thank to past and present residents of House #16: Sylvie, pour l'aide à mon arrivée; Sungeun, for being herself; Ben, for providing a reliable drinking partner; Lisa and Kim, the first Aussies I lived with; Heath, for his formidable Tercel; and finally Octave, for showing me how wonderful life would be if I only had to eat and sleep. I am also indebted to many other past and current residents of the mountain: Uncle Simon, for feeding us all and for a house full or treasures; Mark, for his friendship and good port; and Dave, for an introduction to pit cooking. Thanks of course to all the other students whose friendship I value: Ian, Mary, Oak-Kyoung, Ron, etc. Of course, thanks to all of you, for keeping up with my Frenchism(s)!

I would also like to express my gratitude to the staff and students of the Vatican Observatory Summer School of 1995, for memories which will last a lifetime. Similar thanks also to the various Australian and overseas astronomy students I have met over the years, for wonderful memories.

J'aimerais aussi remercier et reitérer mon amitié à toute la gang de Brossard: Tounic, Lépine, Homsy, Alex, Petit, Tommy, ... Merci surtout pour votre amitié, mais aussi pour avoir enduré mon côté studieux et mes absences fréquentes, et pour avoir gardé contact pendant quatre longues années. Merci d'être vous-mêmes, je ne vous échangerais contre rien au monde. Merci aussi à Jean-François et Quan, pour une amitié profonde et durable.

Of course, special thanks to Makiko, for embarking on a common journey despite the distance separating us. You have enriched my life in more ways than you can imagine.

Finally, a special thank to all the Aussies I have met, for showing me what Australia is all about.

I would also like to acknowledge the financial support of a Canadian NSERC Postgraduate Scholarship, an Australian DEETYA Overseas Postgraduate Research Scholarship, the Astronomical Society of Australia, and of the various institutes I visited and conferences I attended.

Abstract

The main goal of this thesis is to deepen our understanding of the structure and dynamics of bars in spiral galaxies. We first tackle the issue of the pattern speed of bars. We measure directly the bar pattern speed in the galaxy NGC 2915, the first time this is achieved in a late-type gas-rich system. NGC 2915 is a unique object, possessing a blue compact dwarf galaxy core and a H I disk with a bar and spiral arms pattern extending far beyond the optical galaxy. The bar pattern speed is slow, putting corotation at more than 1.7 bar radii, a value incompatible with self-consistent models of barred disks. We demonstrate that the spiral pattern cannot be due to interactions, be sustained by swing amplification, or be driven by the bar. Because the disk of NGC 2915 is dominated by dark matter, we argue that an extensive triaxial dark halo with a slow figure rotation could drive the disk morphology. The existence of such halos is supported by a preliminary analysis of a set of CDM simulations. If our interpretation is right, objects like NGC 2915 offer new opportunities to probe the structure and dynamics of dark halos.

The main part of this thesis is concerned with the vertical structure of bars, and with observational tests of the bar-buckling mechanism for the formation of boxy/peanut-shaped (B/PS) bulges in (edge-on) spiral galaxies. Because bars in edge-on spirals are hard to identify morphologically, we first had to develop bar diagnostics. We use the kinematical signature that a bar imposes on the position-velocity diagram (PVD) of an edge-on disk. We first use periodic orbit families as building blocks to model the structure of real galaxies. We show that the global structure of the PVDs is a reliable bar diagnostic in edge-on disks. Gaps between the signatures of the various periodic orbit families arise in the PVDs due to the non-homogeneous distribution of orbits in a barred disk. We show specifically how the signatures of the x_1 and x_2 families of periodic orbits can be used to determine the viewing angle with respect to the bar.

We also develop bar diagnostics for edge-on disks using hydrodynamical simulations, which specifically target the gaseous component of spiral galaxies. We show that, when a nuclear spiral is formed, associated with the existence of x_2 orbits, the presence of a gap in the PVDs, between the signature of the nuclear spiral and that of the outer parts of the disk, reliably indicates the presence of a bar. This gap is caused by shocks and inflows which lead to depletion of the gas in the outer bar region. The shape of the signature of the nuclear spiral also allows us to determine the viewing angle to the bar.

The last part of this thesis constitutes an extensive observational study of the relationship between bars and B/PS bulges. Using emission line spectroscopy, we search for bars in a large sample of edge-on spiral galaxies with B/PS bulges, and in a smaller control sample of spirals with more spheroidal bulges. We show that almost all B/PS bulges are due to a thick bar viewed edge-on, while only a few extreme cases may be due to the accretion of external material. This strongly supports the bar-buckling mechanism for the formation of B/PS bulges, and implies that accretion plays at most a minor role in the formation of these objects. None of the galaxies in the control sample shows evidence for a bar, which suggests conversely that all bars are B/PS. Studies of this type open up for the first time the possibility of studying observationally the vertical structure of bars. We introduce a number of related ongoing projects before concluding this thesis.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

From ellipticals to dwarfs, galaxies display an amazing variety of morphologies. This is particularly the case for spiral galaxies, where the importance of the bulge, spirals arms, and star formation, all at the core of the Hubble classification of galaxies (Sandage 1961), vary enormously. Although it is less recognised, the bulges of spiral galaxies also show a wide variety of shapes. Boxy and peanut-shaped bulges perhaps form the best known category departing from the classical picture of a spheroidal bulge.

Boxy/peanut-shaped (B/PS) bulges can be distinguished only in edge-on spiral galaxies and are characterised by isophotes which are flat with radius or slightly depressed along the minor axis. This suggests that their vertical structure is significantly different from that of the more spheroidal bulges (Binney & Petrou 1985). In addition, it is now known that spiral galaxies with a B/PS bulge are common, constituting about 20-30% of the spiral galaxy population (see, e.g., Shaw 1987). With the recent discovery that the bulge of the Milky Way is also boxy-shaped (Weiland et al. 1994), it becomes even more important to gain a good understanding of these objects. The core of this thesis is concerned with the development and use of tools to study the three-dimensional structure and dynamics of B/PS bulges, in an attempt to identify their formation mechanism.

As is often the case in astronomy, one can identify phases in the study of B/PS bulges when research focussed on a specific topic and a paradigm was developed. New observational data can topple those paradigms and nurture the rapid progress of new ideas. We may be in such a period now with regard to our understanding of the formation and nature of B/PS bulges.

A chronological approach is well-suited to a review of our knowledge of these fascinating objects. In the next section, the works which laid the foundation for the present study of B/PS bulges will be explored. We will mostly concentrate on the theoretical ideas which were put put forward to explain the formation of B/PS bulges, but will point out, when necessary, observations which either supported, opposed, or prompted these theories. This way, we hope to stress the interplay between theory and observations which guided the evolution of this subject since its beginning.

1.1 The Nature of Boxy/Peanut-Shaped Bulges in Spiral Galaxies: A Historical Perspective

1.1.1 The Recognition of the Boxy/Peanut-Shaped Bulge Phenomenon

It is hard to pinpoint the time when it was first recognised that some spiral galaxies had a bulge with a significant boxy/peanut shape. Burbidge & Burbidge (1959) discussed the unusual shapes of the bulges in NGC 128 (one of the best example of a peanut-shaped bulge), saying that "...NGC 128 is unusual, as its maximum extent perpendicular to the major axis occurs not at the center but at two points symmetrically spaced on either side of the center.", and in NGC 7332, stating that "The shape of the nuclear region is almost rectangular; this galaxy looks intermediate between a normal S0 and NGC 128.". Although they did not use the term B/PS bulge, they had already identified the main property of this class of object. Hodge & Merchant (1966) also noted the "...squareness of the central regions" in their photometric study of NGC 128.

The term "boxy-shaped bulge" maybe due to Sandage (1961) when, in *The Hubble Atlas of Galaxies*, he commented: "NGC 128 has a peculiar box-shaped nucleus." and "NGC 7332 is classed as peculiar because of the box-shaped central regions, ...". On the other hand, many other galaxies in *The Hubble Atlas of Galaxies* have a B/PS bulge but were not labelled as such. For example, about NGC 4565, Sandage said "Note how flat the central cross section of NGC 4565 is.", while no comment on the boxy-shaped bulge of NGC 891, or the peanut-shaped bulge of NGC 4111, was made.

Historically, it is clear that the property of some bulges to appear boxy or peanut-shaped when viewed edge-on was recognised early-on. However, it seems that, at this point, this behaviour was viewed as a peculiarity of no special significance.

1.1.2 The Differentiation of Bulges and Ellipticals

In the early 1970s, a lot of work was devoted to the understanding of the structural and dynamical properties of elliptical galaxies. Prompted mostly by the flattened light distribution of ellipticals, oblate spheroidal models with isotropic velocity dispersions were first constructed (e.g. Lynden-Bell 1962; Prendergast & Tomer 1970). However, it was soon realised (Wilson 1975) that these could not explain the most flattened systems (E5 and later), as they would be unstable to non-axisymmetric perturbations (Ostriker & Peebles 1973). The subject was transformed by kinematical observations which showed that ellipticals rotate too slowly to be rotationally flattened (e.g. Bertola & Capaccioli 1975; Illingworth 1977), and that some have non-zero radial velocity gradients on the minor axis (Bertola & Galletta 1978; Schechter & Gunn 1979). This indicated that ellipticals were oblate spheroids or triaxial ellipsoids with anisotropic velocity dispersions (Binney 1980). While the bulges of spiral galaxies had long been considered close parents of ellipticals, because mostly of the similarities in the light distribution (e.g. Sandage, Freeman, & Stokes 1970), stellar content (e.g. Faber 1977), and kinematics (e.g. Faber & Jackson 1976), these results ultimately changed this view and prompted more detailed studies of bulges.

It was first noted that the light profile of many spiral galaxy bulges did not follow exactly the $R^{1/4}$ law of ellipticals (see, e.g., Kormendy and Bruzual 1978 and Jensen & Thuan 1982 for NGC 4565; Tsikoudi 1980 for NGC 4111). These studies also highlighted the fact that no elliptical galaxy was known (at the time) to possess a B/PS morphology. Furthermore, it was realised that bulges were flatter in the mean than elliptical galaxies (e.g. de Vaucouleurs 1974; Kormendy & Illingworth 1982; see also Kormendy 1980). The result which definitely separated bulges from ellipticals was the realisation that they rotated much more rapidly than the bright ellipticals (see, e.g., Illingworth 1977; Kormendy & Illingworth 1982; Kormendy 1982). Unlike ellipticals, bulges thus appeared to be true rotationally flattened oblate spheroids (see Binney 1976, 1978). Davies et al. (1983) later showed, however, that ellipticals with luminosities comparable to those of bulges had comparable rotation. All these results set the stage for the first comprehensive efforts to model in detail the structure and kinematics of spiral galaxy bulges.

Of particular interest here was the discovery that some of the best known B/PS bulges exhibited cylindrical rotation; i.e. their rotation was independent of the height above the galactic plane (see Kormendy & Illingworth 1982 for NGC 4565; Jarvis 1981 for NGC 128). At this stage, it seemed clear that both the structure and kinematics of B/PS bulges were different from those of "normal" more spheroidal galaxy bulges. In the early 1980s, with the first serious theoretical attempts to understand the formation of B/PS bulges, and then later on with the first systematic studies of the prevalence of these objects, the interest of the B/PS bulge "phenomenon" was finally recognised.

1.1.3 Accretion Scenarios

Jarvis & Freeman (1985a) constructed rotationally flattened axisymmetric models of bulges, using a distribution function based on two integrals of motion, the energy E and angular momentum along the symmetry axis L_z, and an energy cutoff like that of the King (1966) models. Their models reproduced very well the structure and kinematics of spheroidal bulges (Jarvis & Freeman 1985b), but could not account for the cylindrical rotation observed in the B/PS bulges. Jarvis (1981) argued that cylindrical rotators probably require a higher density of material at high L_z in the (E,L_z) plane (close to the boundary defining the circular orbits) than is present in his models, particularly for stars far from the nucleus.

Specifically trying to model B/PS bulges, Rowley (1988) built axisymmetric models based on a two-integral distribution function favouring material on prograde orbits. Contrary to most models at the time, he adopted a truncation depending on both E and L_z, and following a contour of constant density in the (E,L_z) plane. This ensured that his models were cylindrically rotating. Rowley (1986) successfully modelled both kinematical and photometric data for a number of B/PS bulges (although he noted that some bulges were probably mildly triaxial). He argued that the accretion of satellite galaxies by a host spiral was the most likely scenario which could give rise to the distribution function adopted. However, the merger of two similar sized disks could also lead to B/PS bulges in Rowley's (1988) picture; he suggested that this could lead to the larger B/PS bulges.

The work of Binney & Petrou (1985) had an important influence on the way B/PS bulges were thought to form. They constructed a distribution function depending on a third integral of motion, in addition to E and L_z. This third integral generated a higher density of material near a particular plane in action space, which in turn favoured orbits reaching a given height above the galactic plane. These orbits formed tori which appeared B/PS when seen in projection, and cylindrical rotation followed naturally. The models of Binney & Petrou (1985) were not self-consistent, but they provided insight into the structure of (axisymmetric) B/PS bulges. Binney & Petrou (1985) argued that the accretion of satellite galaxies was the ideal way of populating particular regions of action space and thereby forming B/PS bulges. For the accreted material to form a B/PS bulge, the velocity dispersion of the satellite must be much be lower than its orbital speed, and the decay timescale of the orbit must be much longer than the orbital time. This ensures that the accreted material stays clumped in action space.

Following the picture of Binney & Petrou (1985), a range of accretion scenarios could be imagined. However, in order to form a B/PS bulge this way, the range of orbital energies and angular momenta allowed for the accreted material is restricted. It is thus unlikely that several small accreted satellite galaxies would all satisfy this criterion. Remaining satellites should be detectable but they were not observed. Shaw (1987) found that spiral galaxies with a B/PS bulge had no more satellites than spirals with a more spheroidal bulge. The accretion of a single large companion was also excluded, because of the large velocity dispersion and small decay timescale involved, which preclude the clustering of material in action-space. The merger of two spiral galaxies of similar size is another possibility raised by Binney & Petrou (1985). However, Jarvis (1986), Shaw (1987), and de Souza & dos Anjos (1987) showed that B/PS were present in about 20-30% of the entire spiral galaxy population. Because the formation of a B/PS bulge through the merger of two spiral galaxies would require a fairly precise alignment of the spin and orbital angular momenta of the two galaxies, the abundance of these objects makes it an unlikely process (although Rowley 1986 relaxed this condition).

Soon after the work of Binney & Petrou (1985), the accretion of a small number of moderate-sized satellites was left as the only viable accretion scenario to form B/PS bulges. While Shaw (1987) showed that spiral galaxies with a B/PS bulge were not found preferentially in clusters, a cursory examination suggests that the best examples of B/PS bulges are indeed found in small groups (e.g. NGC 128 and ESO 597- G 036). This view was supported by Whitmore & Bell (1988) in another influential paper. They argued that X-shaped structures in spiral galaxies are related to polar-rings, and that both are formed through the accretion of satellite galaxies or external material. While the material in polar-rings is accreted at a nearly perpendicular angle to the disk, they suggested that X-shaped structures could be formed by accreting material at a more oblique angle. Precession is then important, and differential precession spreads the accreted material into a cone, which appears X-shaped in projection. The superposition of the X-shaped structure onto an existing spheroidal bulge will appear B/PS. Their suggestion was supported by the N-body simulations of Hernquist & Quinn (1989), which showed that the accretion of companions on inclined orbits can produce long-lived axisymmetric X-shaped structures.

May, van Albada, & Norman (1985) proposed another mechanism to form B/PS bulges. They showed that a short-lived cylindrical torque, applied to an initially non-rotating prolate triaxial ellipsoid (supported by anisotropic velocity dispersion), leads to an almost axisymmetric rotationally flattened figure with a small figure rotation. Their models appeared clearly B/PS in projection, and the rotation was cylindrical. Although it is not clear how relevant this process might be to the creation of real bulges (the torque is "...merely a convenient experimental device, ..."), similar torques may arise in the early formation stages of galaxies, for example from transient non-axisymmetries in the disks, or from tidal torques during the aggregation process.

While many theoretical ideas involving accretion were put forward during the 1980s, they did not offer clear cut tests of their validity. At that time, observational data were sparse and did not offer a coherent picture of the nature of B/PS bulges. As a consequence, accretion scenarios were generally thought to be an acceptable picture for the formation of these objects.

1.1.4 Bar-Buckling Scenarios

Accretion scenarios were seriously challenged for the first time at the beginning of the 1990s, when it was rediscovered that the three-dimensional (3D) structure of bars tends to evolve toward a boxy/peanut shape when viewed edge-on (Combes et al. 1990; Raha et al. 1991). This idea had been originally proposed by Combes & Sanders (1981) but was neglected. Before we dig deeper into this topic, it is worth retracing the major steps in our understanding of the *two*-dimensional (2D) structure and dynamics of bars. A complete review of barred disks dynamics would take us too far from the issue of B/PS bulges, however, and we refer to the review of Sellwood & Wilkinson (1993) for a more detailed discussion.

The first N-body simulations of rotationally supported stellar disks revealed that they were violently unstable to the formation of large scale bars (e.g. Hockney & Hohl 1969; Miller, Prendergast, & Quirk 1970). These results were confirmed many times over the years, with simulations of ever increasing quality (e.g. Sellwood 1981; Athanassoula & Sellwood 1986). These bi-symmetric instabilities were quickly identified with the dominant linear modes found in stability analyses of axisymmetric disks (Shu 1970; Kalnajs 1971, 1977). The bar instability could be controlled by raising the velocity dispersion in the disk or immersing the galaxy in a massive halo (Ostriker & Peebles 1973). However, this would respectively prevent the propagation of density waves, and imply that galaxies are dark matter dominated even within their optical radii, which is generally not required dynamically (e.g. van Albada & Sancisi 1986). The bars formed in these N-body simulations were fast, ending at or just inside their corotation radius (e.g. Sellwood 1981), although they did slow down slowly with time. They also seemed to match fairly well the observed light distribution of bars (Sparke & Sellwood 1987).

The internal dynamics of barred disks was, and still is, generally explored by studying the orbital structure of model potentials. These are typically composed of a non-axisymmetric component, representing the bar, and some axisymmetric components, representing the disk and halo. The range of mass distributions allowed for bars is constrained by observations, but the bar pattern speed Ω_p is very much a free parameter. Because of the bar potential, the main families of periodic orbits are elongated, and their orientation changes at each major resonance (e.g. Sanders & Huntley 1976). The x_2 family of periodic orbits, elongated perpendicular to the bar, is located inside the inner Lindblad resonances (ILRs); the main family of periodic orbits, the x_1, is elongated parallel to the bar, and is located within corotation (mainly inside the inner ultra-harmonic resonance, IUHR). There are higher order resonance families close to corotation, and periodic orbits around the Lagrange points on the minor axis of the bar, but most are generally thought to be unimportant for the structure of real bars. All these orbit families are mirrored beyond corotation. As the barred component of the potential is made stronger, regions of stochasticity grow around each of the resonances (e.g. Contopoulos & Papayannopoulos 1980). Contopoulos & Grosbøl (1989) provide a more detailed overview of the orbital structure of barred disks. Because self-consistent bars must be supported by the x_1 periodic orbits (and their quasi-periodic analogs), it was realised early-on that bars should end at or just inside corotation (Contopoulos 1980), in agreement with the N-body simulations discussed above. However, nothing formally prevents the bars from having a lower pattern speed.

Most studies mentioned so far considered 2D disks. Because spiral disks are thin, it was thought (despite some evidence for the contrary) that the third dimension was unimportant. James & Sellwood (1978) and Hohl & Zang (1979) carried out some of the first 3D N-body simulations of rotationally supported disks, and noticed that significant vertical structure arose in their models. Combes & Sanders (1981) were the first to notice that the bars in 3D simulations took a B/PS appearance when viewed edge-on. They showed that the thickness of N-body disks increases with time, although this effect could be curbed by a large halo to disk mass ratio. In their models, the bars appeared boxy-shaped when seen end-on and peanut-shaped when seen side-on, and they proposed that this effect could be at the origin of the B/PS bulges seen in many spiral galaxies. Unfortunately, the bar buckling/thickening hypothesis for the formation of B/PS bulges was only half-born at this stage, as their idea was not investigated further for almost 10 years.

The idea resurfaced only after the work of Combes et al. (1990) and Raha et al. (1991). This explains why, despite continuous work on the structure and dynamics of barred spiral galaxies, the idea of forming B/PS bulges through bar-buckling has only taken off in recent years. Using N-body simulations, Combes et al. (1990) showed that bars form and take on a B/PS appearance when viewed edge-on under a large variety of conditions (different numerical schemes, initial mass distributions, initial conditions, etc.). All the bars thickened soon after forming, ending close to corotation once an equilibrium state was reached. This work established that bar formation and thickening is a generic property of rotationally supported stellar disks. Combes et al. (1990) also generated two-dimensional velocity and velocity dispersion fields, and showed that cylindrical rotation is confined to the brightest parts of the bar/bulge. Raha et al. (1991) reported on similar simulations. However, they showed that in an initially thin disk, the buckling of a bar out of the plane of the galaxy can be so violent as to seriously disrupt and weaken it. Bars form, buckle, and then settle with an increased thickness and velocity dispersion. They suggested that such violent buckling may be able to totally destroy a bar, and could explain the relatively low fraction of barred spiral galaxies observed (i.e. why many galaxies are not barred). They also provided snapshots of the disks in the act of bending, with strong saddle shapes. These strongly support the idea that the thickening of the disks is due to the buckling instability.

Toomre (1966) was the first to study the buckling of disks. He showed that if the vertical velocity dispersion in a disk is less than about a third of the velocity dispersion in the plane, the disk will be unstable to buckling modes (fire-hose or buckling instability). Toomre's (1966) results were later confirmed by many authors (e.g. Fridman & Polyachenko 1984; Araki 1985). Bar formation in a disk makes the orbits within the bar more eccentric, without affecting much their vertical motions, and thus provides a natural mechanism for the bar to buckle. Combes & Sanders (1981) and Combes et al. (1990) developed an alternative idea for the thickening of bars. They suggested that resonances between the rotation of the bar (Ω_p) and the vertical oscillations of the stars (ν_z) could also make the disk vertically unstable (see also Binney 1981). They noticed that the maximum vertical excursion of the stars in their models occured at the position of both the horizontal ILR ($\Omega_p = \Omega - \kappa/2$, where κ is the epicyclic frequency) and the vertical ILR ($\Omega_p = \Omega - \nu_z/2$), implying that $\kappa \approx \nu_z$ where the boxy/peanut shape is strongest. The buckling instability and the mechanism proposed by Combes et al. (1990) are likely to be complementary processes in the thickening of bars.

Many studies of the 3D orbital structure of non-rotating or slowly rotating triaxial ellipsoids exist, in the context of elliptical galaxies, but their relevance to rapidly rotating bars in disks is far from clear (see, e.g., de Zeeuw & Franx 1991 for a review). Pfenniger (1984) showed that the x_1 orbits, the main family of periodic orbits in 2D barred disks, developed regions of vertical instability when allowed to move in the third dimension. These regions grew as the bar was made thinner. Pfenniger and Friedli (1991) studied the orbital structure in one of the Combes et al. (1990) models. They showed that most stars in the B/PS bar are trapped around orbits of the 2:2:1 family, the 3D generalisation of the x_1 family (2 radial oscillations and 2 vertical oscillations during one revolution). This is probably the case no matter how the bar thickened. Pfenniger (1985) further demonstrated that chaotic motions associated with the vertical instabilities can populate the bulges by semi-ergodic diffusion.

The body of theoretical and modelling work now supporting the buckling and thickening of bars makes this a very appealing mechanism to explain the formation of B/PS bulges in spiral galaxies. However, observational confirmations of this hypothesis are few. Only in a few cases can a bar be directly associated with a B/PS bulge, based on the morphology of the system alone (see, e.g., Bettoni & Galletta 1994 for NGC 4442). The best evidence in favour of the bar-buckling scenario perhaps comes from our own Milky Way. It is now well established that the Galactic bulge is boxy (Weiland et al. 1994) and there is mounting evidence that it is bar-like (see Kuijken 1996 for a recent review). Further support for the bar-buckling mechanism comes from the statistics of the prevalence of these objects, which show that B/PS bulges are present in 20-30% of edge-on spirals (Jarvis 1986; Shaw 1987; de Souza & dos Anjos 1987). This number is consistent with the fraction of strongly barred spirals in more face-on systems (e.g. Sellwood & Wilkinson 1993). The fraction of boxy versus peanut-shaped bulges is also consistent with that predicted from N-body simulations (Combes et al. 1990). Perhaps more importantly, bar-buckling offers a natural way to form B/PS bulges in isolated systems. We recall that B/PS bulges are not found preferentially in clusters (Shaw 1987). Another point in favour of the bar-buckling scenario is that cylindrical rotation is present naturally in all the models. Nevertheless, these arguments are rather indirect. Beside the recent work of Kuijken & Merrifield (1995), which we will discuss in the next section, very little direct confirmation of the validity or the bar-buckling scenario exists.

Forming B/PS bulges out of bars also has some possible drawbacks, although none of these appear particularly threatening at the moment. The general impression one gets from the examination of spirals with a B/PS bulge is that the bulges are shorter, relative to the disk diameter, than the bars seen in face-on systems or the strong bars formed in N-body simulations. However, simple projection effects could easily explain these differences (a given surface-brightness level is reached at a smaller radius in a more face-on disk), and no proper statistics exist. The secular evolution of bars is also poorly known and the subject of many current studies. For examples, bars could be seriously affected by interaction with the disk or a massive spheroidal component, as suggested by Sellwood (1980, 1981) and Weinberg (1985), who studied the transfer of angular momentum between these components. Recent simulations by Debattista & Sellwood (1998) suggest, however, that even though the bar can be slowed down if a dark halo dominates the inner parts of the disk (which, again, is not expected), the bar continues to grow and preserve its boxy/peanut shape. Some efforts have also been directed toward the understanding of mechanisms which have the potential of destroying bars, particularly the growth of a central mass concentration (e.g. Hasan & Norman 1990; Friedli & Benz 1993). However, the destruction of a bar through this mechanism also destroys the boxy/peanut shape (Norman, Sellwood, & Hasan 1996), so it is not inconsistent with the idea of a connection between bars and B/PS bulges.

There are also "hybrid" scenarios for the formation of B/PS bulges. Noguchi (1987) first suggested that interaction can provide a very efficient mechanism to initiate bar formation in disk galaxies. He showed that, in the case of parabolic prograde encounters, his N-body disks had a tendency to form well-developed spiral structures, with strong bar-like patterns in the inner regions. Gerin, Combes, & Athanassoula (1990) also showed that interaction can accelerate bar formation in a disk which is marginally stable. The bar growth rate and final shape are affected by the sense of the interaction (prograde versus retrograde), as well as the strength and pattern speed of the resulting bar (to a lesser extent). Of course, once a bar is formed in this way, it is free to evolve to a boxy/peanut shape in the manner described above (see Mihos et al. 1995). Hybrid scenarios thus couple the accretion and bar-buckling mechanisms. However, hybrid scenarios are really bar-buckling scenarios: interactions initiate bar formation, but the shape of the resulting bar, the issue of interest here, is really due to the subsequent buckling and thickening of the bar.

1.2 Current Status and Thesis Outline

1.2.1 The Pattern Speed of Bars

As we stressed in the our discussion of the structure and dynamics of 2D barred disks, little information is available to constrain the pattern speed of bars. N-body simulations of rotationally supported stellar disks generally yield fast rotating bars, that is bars which end at or just inside their corotation radius (e.g. Sellwood 1981). This view is supported by studies of the orbital structure of barred disks (e.g. Contopoulos 1980), but nothing formally prevents the bars from having a slower pattern speed.

Observationally, it is very difficult to measure the pattern speed of bars. Many methods exist, but only two are widely used. The first method, based on the theory of resonance ring formation pioneered by Schwarz (1981, 1984; see also Byrd et al. 1994), relies on the association of rings in the disk of barred spirals with the location of known resonances. A measurement of the circular velocity curve (usually taken to be the observed rotation curve) then allows to infer the pattern speed. In the second method, the gas flow in a barred spiral galaxy is compared with a series of hydrodynamical models in which the pattern speed of the bar is a free parameter. The best fit model then yields an estimate of the bar pattern speed (see, e.g., Sanders & Tubbs 1980 and Duval & Athanassoula 1983 for early models of NGC 5383). These methods rely on theory and are therefore rather indirect. Tremaine & Weinberg (1984) proposed the only direct method, relying on little theory and observable quantities alone. Unfortunately, the application of the method is very difficult, and it has only been used with success on one object (see Kent 1987; Merrifield & Kuijken 1995).

The above methods have yielded measurements which are generally in agreement with the view that bars are fast rotators. However, most of the evidence is indirect (in the above sense) and, until more bars have their pattern speed directly measured, the issue remains open. Furthermore, both N-body simulations and observational studies have focussed on systems with strong bars, representative of barred spirals of intermediate and early type. Our knowledge of the pattern speed of bars in late-type galaxies is still rudimentary. With recent suggestions that such bars may rotate slowly, with corotation far in the disk (see Elmegreen 1996 for a review of the issue), it has become pressing to obtain direct measurements of the bar pattern speed in range of objects, particularly in late-type spirals. Chapter 2 of this thesis constitutes a small step in that direction.

In Chapter 2, we measure the pattern speed of NGC 2915, a blue compact dwarf (BCD) galaxy with a very extended H I disk (see Meurer, Mackie, & Carignan 1994; Meurer et al. 1996). This gaseous disk extends out to 22 optical scale-lengths and displays a strong spiral structure with a short central bar. We show that the measured pattern speed puts corotation at more than 1.7 bar radii, a value incompatible with self-consistent models of rotationally supported disks. Furthermore, we show that the spiral pattern is unlikely to be caused by interaction, be sustained by swing amplification (Toomre 1981), or be driven by the bar. It may therefore be caused by dark matter, which is known to dominate the dynamics of the system at all radii (Meurer et al. 1996). We reject the possibility of dark matter distributed in a disk, but argue that a massive and extended triaxial dark halo with a slow figure rotation could drive the observed H I structure. We associate the pattern speed of the H I disk with the figure rotation of this dark halo. If this is correct, galaxies like NGC 2915 may provide a new way to study the properties of triaxial dark halos, which is a subject of cosmological significance (see Chap. 2).

1.2.2 The Relationship Between Bars and Boxy/Peanut-Shaped Bulges

Our historical review of the evolution of our knowledge concerning B/PS bulges reflected current ideas about the formation of these objects. Theories of formation for B/PS bulges can loosely be put into two groups: accretion scenarios and bar-buckling scenarios.

The review of accretion mechanisms highlighted many problems of these theories. Most importantly, the range of impact parameters allowed for the accreted material in order to form a B/PS bulge is very restricted (e.g. Binney & Petrou

1985). We argued that the only viable accretion scenario is through the accretion of a small number of intermediate size satellites. Therefore, while it is likely that accretion plays a role in the formation of *some* B/PS bulges, it is unlikely to be the primary formation mechanism. Our approach in this thesis will reflect this view. While we do not specifically target accretion, we will address relevant issues when appropriate.

At this stage, we believe that the emphasis of any study of B/PS bulges should be on testing the bar-buckling scenario. N-body simulations strongly suggest that the buckling and thickening of bars, and the resulting boxy/peanut shape, are a generic property of barred disks (e.g. Combes et al. 1990). Orbital studies in 3D support this view and can explain the final shape of the bars in term of orbit trapping about the 2:2:1 periodic orbit family (e.g. Pfenniger & Friedli 1991). The body of theoretical and modelling work supporting the bar-buckling mechanism for the formation of B/PS bulges is thus extensive and solid. At the moment, the main problem facing buckling scenarios is the lack of observational support. Most evidence in favour of bar-buckling are weak and statistical in nature (e.g. Shaw 1987), and a direct connection between B/PS bulges and bars has been hard to come by. Unfortunately, it is difficult to identify bars in edge-on spirals, where B/PS bulges are most easily seen. The methods used in the past, such as the association of a plateau in the light profile of an edge-on disk with the presence of a bar (e.g. de Carvalho & da Costa 1987), are insecure. A large part of this thesis, Chapters 3 and 4, will thus be devoted to the development of reliable bar diagnostics in edge-on disks. Chapter 5 will make use of these diagnostics to directly test the relationship between bars and B/PS bulges, using a large sample of edge-on spiral galaxies with and without a B/PS bulge.

Kuijken & Merrifield (1995; see also Merrifield 1996) first demonstrated that a kinematical identification of bars in external edge-on spiral galaxies was possible. They showed that periodic orbits in an edge-on barred disk produce characteristic double-peaked line-of-sight velocity distributions, which can then be used to identify an edge-on spiral as barred. In Chapter 3, we refine and develop further the method proposed by Kuijken & Merrifield (1995). We use periodic orbit families as building blocks to model real barred galaxies. We show that the global structure of the position-velocity diagrams (PVDs; i.e. the density of projected material as a function of line-of-sight velocity and projected position) can be used reliably as a bar diagnostic in edge-on disks. The presence of gaps in the PVDs is a direct consequence of the non-homogeneous distribution of orbits in a barred galaxy. We also discuss how the signatures of particular families of periodic orbits can be used to determine the viewing angle with respect to the bar, and to a lesser extent to constrain the mass distribution of an observed galaxy.

In Chapter 4, we develop analogous bar diagnostics specifically for the gas component of spiral galaxies. For that, we use hydrodynamical simulations of barred disks where the gas is treated as test particles (Athanassoula 1992). We show that when a nuclear spiral is formed, corresponding to the existence of an ILR, the presence of gaps in the PVDs between the signature of the nuclear spiral and that of the outer parts of the disk reliably indicates the presence of a bar. These gaps are due to the presence of shocks and inflows in the simulations, which lead to a depletion of the gas in the main and outer bar regions. The shape of the signature of the nuclear spiral can also be used to determine the viewing angle to the bar. These diagnostics are not applicable if no nuclear spiral is present. However, the presence (or absence) of a nuclear spiral puts strong constraints on the properties of an observed galaxy.

In Chapter 5, we present a systematic study of the relationship between bars and B/PS bulges in spiral galaxies. We use the diagnostics developed in Chapters 3 and 4 to search for bars in a large sample of edge-on spiral galaxies with B/PS bulges, and in a smaller control sample of edge-on spirals with more spheroidal bulges. We show that almost all B/PS bulges are due to a thick bar viewed edge-on, while only a few extreme cases may be due to accretion. None of the galaxies in the control sample show evidence for a bar, which suggests conversely that all bars are B/PS. These results strongly support the bar-buckling mechanism for the formation of B/PS bulges.

In Chapter 6, we summarise our results and describe work in progress which is relevant to this thesis. Finally, we discuss some ideas for future work, and describe some interesting spin-offs that this study might have in other fields.

References

Araki, S. 1985, Ph.D. Thesis, Massachusetts Institute of Technology

Athanassoula, E. 1992, MNRAS, 259, 345

Athanassoula, E., & Sellwood, J. A. 1986, MNRAS, 221, 213

Bertola, F., & Capaccioli, M. 1975, ApJ, 200, 439

Bertola, F., & Galletta, G. 1978, ApJ, 226, L115

Bettoni, D., & Galletta, G. 1994, A&A, 281, 1

Binney, J. J. 1976, MNRAS, 177, 19

———. 1978, MNRAS, 183, 501

———. 1980, Phil. Trans. R. Soc. London, 296, 329

———. 1981, MNRAS, 196, 455

Binney, J., & Petrou, M. 1985, MNRAS, 214 449

Burbidge, E. M., & Burbidge, G. R. 1959, ApJ, 130, 20

Byrd, G., Rautiainen, P., Salo, H., Buta, R., & Crocker, D. A. 1994, AJ, 108, 476

Combes, F., Debbasch, F., Friedli, D., & Pfenniger, D. 1990, A&A, 233, 82

Combes, F., & Sanders, R. H. 1981, A&A, 96, 164

Contopoulos, G. 1980, A&A, 81, 198

Contopoulos, G., & Grosbøl, P. 1989, A&A Rev., 1, 261

Contopoulos, G., & Papayannopoulos, T. 1980, A&A, 92, 33

Davies, R. L., Efstathiou, G., Fall, S., Illingworth, G., & Schechter, P. L. 1983, ApJ, 266, 41

Debattista, V. P., & Sellwood, J. A. 1998, ApJ, 493, L5

de Carvalho, R. R., & da Costa, L. N. 1987, A&A, 171, 66

de Souza, R. E., & dos Anjos, S. 1987, A&AS, 70, 465

de Vaucouleurs, G. 1974, in The Formation and Dynamics of Galaxies, ed. J. R. Shakeshaft (Boston:Reidel), 1

de Zeeuw, T., & Franx, M. 1991, ARA&A, 29, 239

Duval, M. F., & Athanassoula, E. 1983, A&A, 121, 297

Elmegreen, E. 1996, in Barred Galaxies, ed. R. Buta, D. A. Crocker, and B. G. Elmegreen (ASP: San Francisco), 505

Faber, S. M. 1977, in The Evolution of Galaxies and Stellar Populations, eds. B. M. Tinsley & R. B. Larson (New Haven: Yale University Observatory), 157

Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668

Fridman, A. M., & Polyachenko, V. L. 1984, Physics of Gravitating Systems (New York: Springer-Verlag)

Friedli, D., & Benz, W. 1993, A&A, 268, 65

Gerin, M., Combes, F., & Athanassoula, E. 1990, A&A, 230, 37

Hasan, H., & Norman, C. 1990, ApJ, 361, 69

Hernquist, L., & Quinn, P. J. 1989, ApJ, 342, 1

Hockney, R. W., & Hohl, F. 1969, AJ, 74, 1102

Hodge, P. W., & Merchant, A. E. 1966, ApJ, 144, 875

Hohl, F., & Zang, T. A. 1979, AJ, 84, 585

Illingworth, G. 1977, ApJ, 218, L43

James, R. A., & Sellwood, J. A. 1978, MNRAS, 182, 331

Jarvis, B. J. 1981, Ph. D. Thesis, The Australian National University

———. 1986, AJ, 91, 65

Jarvis, B. J., & Freeman, K. C. 1985a, ApJ, 295, 314

———. 1985b, ApJ, 295, 324

Jensen, E. B., & Thuan, T. X. 1982, ApJS, 50, 421

Kalnajs, A. J. 1971, ApJ, 166, 275

———. 1977, ApJ, 212, 637

Kent, S. M. 1987, AJ, 93, 1062

King, I. R. 1966, AJ, 71, 64

Kormendy, J. 1980, in Proceedings of ESO Workshop on Two-Dimensional Photometry, ed. P. Crane & K. Kjär (Genava:ESO), 191

———. 1982, ApJ, 257, 75

Kormendy, J., & Bruzual, A. G. 1978, ApJ, 223, L63

Kormendy, J., & Illingworth, G. 1982, ApJ, 256. 460

Kuijken, K. 1996, in Barred Galaxies, ed. R. Buta, D. A. Crocker, and B. G. Elmegreen (ASP: San Francisco), 505

Kuijken, K., & Merrifield, M. R. 1995, ApJ, 443, L13

Lynden-Bell, D. 1962, MNRAS, 123, 447

May, A., van Albada, T. S., & Norman, C. A. 1985, MNRAS, 214 131

Merrifield, M. R. 1996, in Barred Galaxies, ed. R. Buta, D. A. Crocker, and B. G. Elmegreen (ASP: San Francisco), 179

Merrifield, M. R., & Kuijken K. 1995, MNRAS, 274, 933

Meurer, G. R., Carignan, C., Beaulieu, S. F., & Freeman, K. C. 1996, AJ, 111, 1551

Meurer, G. R., Mackie, G., & Carignan, C. 1994, AJ, 107, 2021

Miller, R. H., Prendergast, K. H., & Quirk, W. J. 1970, ApJ, 161, 903

Mihos, J. C., Walker, I. R., Hernquist, L., de Oliveira, M. C., & Bolte, M. 1995, ApJ, 447, L87

Noguchi, M. 1987, MNRAS, 228, 635

Norman, C. A., Sellwood, J. A., & Hasan, H. 1996, ApJ, 462, 114

Ostriker, J. P., & Peebles, P. J. E. 1973, ApJ, 186, 467

Pfenniger, D. 1984, A&A, 134, 373

———. 1985, A&A, 150, 112

Pfenniger, D., & Friedli, D. 1991, A&A, 252, 75

Prendergast, K. H., & Tomer, E. 1970, AJ, 75, 674

Raha, N., Sellwood, J. A., James, R. A., & Kahn, F. D. 1991, Nature, 352, 411

Rowley, G. 1986, Ph.D. Thesis, The Australian National University

———. 1988, ApJ, 331, 124

Sandage, A. 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Institution)

Sandage, A., Freeman, K. C., & Stokes, N. R. 1970, ApJ, 160, 831

Sanders, R. H., & Huntley, J. M. 1976, ApJ, 209, 53

Sanders, R. H., & Tubbs, A. D. 1980, ApJ, 235, 803

Sellwood, J. A. 1980, A&A, 89, 296

———. 1981, A&A, 99, 362

Sellwood, J. A., & Wilkinson, A. 1993, Rep. Prog. Phys., 56, 173

Schechter, P. L., & Gunn, J. E. 1979, ApJ, 229, 472

Schwarz, M. P. 1981, ApJ, 247, 77

———. 1984, MNRAS, 209, 93

Shaw, M. A. 1987, MNRAS, 229, 691

Shu, F. H. 1970, ApJ, 160, 89

Sparke, L. S., & Sellwood, J. A. 1987, MNRAS, 225, 653

Toomre, A. 1966, in Geophysical Fluid Dynamics, 1966 Summer Study Program at Woods Hole Oceanographic Institution, ref. no. 66-46, 111

———. 1981, in Structure and Evolution of Normal Galaxies, ed. S. M. Fall & D. Lynden-Bell (Cambridge: Cambridge University Press), 111

Tremaine, S., & Weinberg, M. D. 1984, ApJ, 282, L5

Tsikoudi, V. 1980, ApJS, 43, 365

van Albada, T. S., & Sancisi, R. 1986, Phil. Trans. R. Soc. London A, 320, 447

Weiland, J. L., et al. 1994, ApJ, 425, L81

Weinberg, M. D. 1985, MNRAS, 213, 451

Whitmore, B. C., & Bell, M. 1988, ApJ, 324, 741

Wilson, C. P. 1975, AJ, 80, 175