Chapter 6

Conclusion

Each chapter of this thesis contains an abstract and a conclusion with a summary of its main results, and it would be too repetitive to provide yet another summary in this chapter. We will thus recall only the main achievements of each chapter and their importance in the next section. We then describe some ongoing projects aimed at increasing our understanding of spiral galaxies with a boxy/peanut-shaped (B/PS) bulge, but which are still incomplete. In the last section, we discuss possible applications of the methods used in this thesis to other fields of astronomy, in particular to the study of the structure and dynamics of other galaxy types.

6.1 Summary of Main Results

In Chapter 2, we successfully measured the pattern speed of the H I disk in the galaxy NGC 2915, using the method proposed by Tremaine & Weinberg (1984). This is only the second direct measurement of a bar pattern speed, and the first one in a gas-rich galaxy. NGC 2915 is a unique object, with a blue compact dwarf galaxy "core" and a very extended H I disk (Meurer, Mackie, & Carignan 1994; Meurer et al. 1996). This disk shows a strong bar and a well-developed spiral pattern. We demonstrated that the bar pattern speed is slow, too slow to be consistent with models of self-gravitating disks. NGC 2915 is dynamically dominated by dark matter (Meurer et al. 1996), and we argued that the structure and kinematics of the disk could be explained by the effects of an extended triaxial halo with a slowly rotating figure. If we are right, systems such as NGC 2915 could helps us constrain the geometry and dynamics of dark halos, and may at the same time provide important constraints on cosmological structure formation scenarios.

In the following chapters, we concentrated on testing the possible relationship between bars and B/PS bulges. Such a relationship should exist if bar-buckling is the dominant formation mechanism for these objects. In order to achieve this goal, we developed methods to identify bars in edge-on spiral galaxies. Following the work of Kuijken & Merrifield (1995), we adopted in Chapter 3 an approach based on periodic orbits, considering periodic orbit families as building blocks to model real galaxies. We showed that the global structure of the position-velocity diagrams (PVDs), derived using an edge-on projection, is a reliable bar diagnostic in edge-on disks. In particular, the non-homogeneous distribution of the orbits in a barred galaxy creates characteristic gaps in the PVDs, between the signatures of the various families of periodic orbits. Although periodic orbits are only an approximation to the structure and kinematics of a real galaxy, they provide insight into the properties of real systems, and are an invaluable tool for the development and understanding of more complex and realistic models.

In Chapter 4, we developed better bar diagnostics for edge-on spirals, using hydrodynamical simulations which specifically target the gaseous disk component (see Athanassoula 1992). We showed that, when a nuclear spiral is formed, gaps appear in the PVDs between the signature of the nuclear spiral and that of the outer parts of the disk. The gaps dominate the structure of the PVDs, and are a good bar diagnostic to be used with real observations, where the spatial and spectral resolutions are often limited. The shape of the signature of the nuclear spiral can also be used to determine the viewing angle with respect to the bar.

In Chapter 5, we used our diagnostics to study the relationship between bars and B/PS bulges. We searched for bars in a large sample of edge-on spiral galaxies with a B/PS bulge, and in a smaller sample of edge-on galaxies with a more spheroidal bulge. We showed that most 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 their formation. None of the galaxies in the control sample were barred, which suggests in addition that most bars are B/PS.

The observations presented in Chapter 5 demonstrate the power of the diagnostics developed. These can now be used as a simple tool for a range of other studies. In particular, by providing an easy way to identify bars in edge-on spiral galaxies, they allow us to study the influence of bars on the vertical structure of disks. Observationally, this has never been possible before.

6.2 Work in Progress

The observations presented in Chapter 5 represent only a subset of the data collected during this thesis. For all the sample galaxies, we have also obtained long-slit absorption line spectroscopic data, near-infrared (NIR) K-band imaging data, and optical BVI-band images. We have also acquired H I radio synthesis data for a small number of objects. We will now discuss the status and goals of these observations, as well as the status of other related projects.

6.2.1 Penetrating the Dust Barrier: H I Line-Imaging

To study the vertical light distribution of bars/bulges, it is preferable to use galaxies which are as edge-on as possible. This reduces problems associated with deprojecting the light distribution of slightly inclined systems, and with removing contaminating disk light from the bulges. However, as we discussed in Chapter 5, dust can reduce our ability to identify bars in perfectly edge-on systems, especially if they have a strong dust lane. The solution is to apply the bar diagnostics in regions of the spectrum which are less affected by dust.

Because spiral disks are probably optically thin at K-band (see Byun 1992), the NIR H Brγ line would be well-suited for this type of work, but the line is weak in most galaxies and NIR spectrographs with adequate resolution are not common. Another solution is to use H I line-imaging observations with a radio synthesis telescope. It is then possible to obtain PVDs through dust lanes, with a higher spectral resolution than possible optically. In addition, because of the full 2D spatial coverage, such data provide a better observational handle on possible interaction and/or accretion of material. Using the Australia Telescope Compact Array (ATCA), we have surveyed 10 objects in our sample for H I, focussing on the largest and more dusty galaxies with $\delta \lesssim -24°$ (to obtain a full uv coverage with the ATCA). Because the bar diagnostics developed require relatively high spatial resolution, we had to use the longest but least sensitive arrays (6 km). We detected 4 galaxies: IC 2531, NGC 6771, ESO 240- G 011, and NGC 5084. For each of these galaxies, we have now acquired a complete data set, consisting of observations in three different configurations (2×6 km, 1×1.5 km).

The goal of these observations is similar to that of the emission line spectroscopy presented in Chapter 5. Our main aim is to verify the presence of a bar in the edge-on disks. For IC 2531, this has already proven successful. The optical observations showed a featureless PVD, but a bar signature is clearly visible in the H I data (see Bureau & Freeman 1997a for preliminary results). It will also be interesting to compare the PVDs obtained in H I with those obtained from the ionised gas (Ch. 5), as each traces a different phase of the interstellar medium. In addition, as mentioned above, the H I observations provide us with a better way to evaluate the importance of interaction/accretion in the systems. In that regard, NGC 6771 and NGC 5084 will be particularly useful, as there is already independent evidence for interaction in these systems. The observations can also be used to study issues outside of the main emphasis of this thesis. For example, they can be used to study the warping and flaring of the H I layer in the outer parts of the disks (see, e.g., Olling 1995, 1996). The analysis of these observations is, however, in a preliminary state. We will report on our results in a future paper.

6.2.2 Stellar Diagnostics: Absorption Line Spectroscopy

The bar diagnostics developed in Chapter 4 were targeted specifically at the gaseous component of spiral galaxies. Because many of the features in the PVDs are due to the collisional nature of gas (the presence of shocks), it is not possible to use these diagnostics directly to interpret stellar spectra. The periodic orbits approach used in Chapter 3 probably provides a better approximation to the stellar kinematics. However, even this approach is unsatisfactory at a quantitative level, because stars are not restricted to move on periodic orbits. Most stars are probably simply trapped around these orbits and, in some circumstances, there may be a significant numbers of stars on irregular (chaotic) orbits (see, e.g., Sellwood & Wilkinson 1993). We thus expect the PVDs produced in Chapter 3 to appear "washed out" in more realistic stellar models.

In collaboration with E. Athanassoula, we have begun a project to produce bar diagnostics in edge-on spiral galaxies based on the stellar kinematics, in a manner analogous to that of Chapter 4 with the gas kinematics. For that, we are using the results of a small number of 3D N-body simulations of rotationally supported disks. As in the simulations reported by other groups (e.g. Combes et al. 1990), these disks rapidly form bars which buckle and settle with a boxy/peanut shape. By projecting these models edge-on, we are able to produce PVDs analogous to those of Chapters 3 and 4. These will allow us to design proper bar diagnostics to be used in conjunction with stellar kinematical observations. In addition, these models will enable us to quantify how much the bar signature changes as the disk is inclined. We have conducted a preliminary analysis of some PVDs, but a more thorough investigation is required before we report on these results.

On the observational side, we have obtained absorption line spectroscopic data for all the sample galaxies, simultaneously with the emission line data described in Chapter 5. The blue arm of the spectrograph was centered on the Mg b absorption feature ($\lambda5190$) and, when no emission line was detected, the red arm of the spectrograph was moved to the Ca II absorption line triplet ($\lambda8600$). It will be interesting to compare the stellar kinematics in the sample galaxies with those predicted from the N-body models described above. In particular, for the sample galaxies with no or confined emission lines (see Table 5.3), where the diagnostics developed in Chapter 4 could not be used, we will now be able to verify whether or not the disks harbour a bar. This will extend the work described in Chapter 5 to the whole galaxy sample, and will hopefully strengthen our conclusions concerning the origin of B/PS bulges. The analysis of the absorption line spectra is still underway, and, again, we will report on these at a later date.

6.2.3 The Vertical Structure of Bars: K-Band Imaging

The N-body simulations discussed in the previous section have wider applications than the simple development of bar diagnostics for the stellar component of spiral galaxies. By quantifying the boxiness of the bulges (e.g. Athanassoula et al. 1990), we will be able to study how the bar/bulge shape varies with the inclination of the disk and the viewing angle to the bar. This will put better constraints on the likelihood of detecting B/PS bulges for various lines-of-sight, and will thus provide a better comparison for existing surveys (e.g. Shaw 1987), and for observations of individual systems.

We have also obtained K-band imaging data for all the sample galaxies, using CASPIR (Cryogenic Array SPectrometer/ImageR) on the 2.3 m telescope at Siding Spring Observatory. These will be used to construct mosaiced images of the galaxies, each galaxy requiring mosaicing of 2–5 CASPIR fields aligned with the major axis (the individual fields are about $2' \times 2'$). The use of K-band data is essential to reduce the effects of dust, especially for galaxies with a strong dust lane (see Kuchinski & Terndrup 1996).

Our observations have two main goals. Firstly, we aim to obtain an improved classification of the morphology of the bulges for the sample galaxies (boxy versus peanut-shaped), compared to that of Chapter 5. In conjunction with the observed PVDs, the K-band images will thus provide a strong test of the bar-buckling scenario for the formation of B/PS bulges, which predicts that the bulges appear boxy-shaped when the bar is seen close to end-on and peanut-shaped when the bar is seen close to side-on (see, e.g., Combes et al. 1990).

Secondly, we aim to study the vertical structure of bars. Observationally, this has never been done before, mostly because no reliable bar diagnostic in edge-on spiral galaxies was available. Our primary goal is to compare the observed vertical light distribution of bars with that predicted from 3D N-body simulations of rotationally supported disks. These predict vertical light profiles which are closer to an exponential law than to the usual $R^{1/4}$ law of spheroidal bulges (see Combes et al. 1990). In addition, because we know the orientation of the bars (approximately), we should be able to constrain their 3D light distribution. Thus, for the first time, we will be able to seriously test observationally 3D models of barred spiral galaxies. Furthermore, using our sample, we will be able to contrast the vertical light distribution of barred and unbarred systems. Finally, we will be able to study how the shape and scaleheight of bars vary with both radius and Hubble type (see, e.g., Burkert & Yoshii 1996). Although all the K-band imaging data have been acquired, none have been reduced or analysed, so we cannot report any results at this point.

6.2.4 Stellar Populations: Optical Imaging

The bar-buckling scenario for the formation of B/PS bulges invites a comparison of the stellar populations of the bar and disk once the bar has reached a steady state. In order to study this issue, we have obtained optical BVI broadband images for all our sample galaxies (see Just, Fuchs, & Wielen 1996), using the 1 m telescope at Siding Spring Observatory (direct imaging). Adding U-band data would be a significant enhancement, as it would help break the age-metallicity degeneracy. However, we recognise that the data for many objects will be seriously affected by dust, especially close to the plane. Again, none of these data have been analysed yet.

6.3 Future Work

The diagnostics developed in Chapters 3 and 4, and the results reported Chapters 2 and 5, encourage more work. Several aspects of our study of B/PS bulges should be deepened, while some interesting prospects are raised for the study of other types of galaxies. We discuss some potential projects in the next two sections.

6.3.1 Spiral Galaxies

In the spirit of Chapter 2, it would be extremely valuable to have more direct determinations of the pattern speed in barred spiral galaxies. The bar pattern speed is one of the most important parameters determining the structure and dynamics of barred spirals. Only with more direct measurements will we be able to test if our current models of barred disks are correct. Direct measurements of the bar pattern speed are required in both early-type and late-type spirals. However, because little secure knowledge on pattern speeds in late-type spirals has been gained from theory, the need is more urgent for these objects (see Elmegreen 1996). Now that we have demonstrated that H I observations can be used with the Tremaine-Weinberg (1984) method, at least for some objects, the situation for late-type spiral is more promising.

Some of the barred galaxies studied in Chapter 5 possess ionised gas PVDs with a great amount of structure (see, e.g., NGC 5746 in Fig. 5.1). Modelling these systems individually would be particularly rewarding. Not only would it enable us to constrain the mass distributions and bar pattern speeds very well (see Ch. 4), but we would also learn greatly about the effects of the bars on the interstellar medium, particularly in the central regions of the galaxies, near the ILRs. In the same spirit, it would be worthwhile to acquire 2D stellar kinematical data for a few objects (or, at least, obtain kinematical data away from the plane). These would allow a detailed comparison of the observed kinematics with that predicted from N-body simulations (see, e.g., Combes et al. 1990). In particular, it would allow a thorough investigation of cylindrical rotation in B/PS bulges, which has been predicted to stop outside of the brightest parts of the bar/bulge (see, again, Combes et al. 1990). With the advent of integral field spectrographs with relatively large fields (e.g. $30'' \times 30''$ for SAURON), such projects are becoming more realistic.

The idea of "bars within bars" has received a lot of attention in recent years. Many spiral galaxies with multiple triaxial structures have been observed (e.g. Wozniak et al. 1995) and it has been suggested that such structures could provide an efficient way to feed active galactic nuclei (see, e.g., Shlosman, Frank, & Begelman 1989). It would be worthwhile to develop multiple-bar diagnostics for edge-on spiral galaxies in a manner analogous to that of Chapters 3 and 4. The unique line-of-sight to edge-on spirals allows us to capture the kinematics of whole disks using simple long-slit spectroscopy, and would allow us to trace flows of material in the galaxies on various scales. N-body simulations (including gas) and periodic orbit studies of these object now exist (e.g. Friedli & Martinet 1993; Maciejewski & Sparke 1997), so the development of such diagnostics should be straightforward.

While we have shown in Chapter 5 that B/PS bulges in spiral galaxies are due to the presence of an edge-on bar, we could not determine how these bars formed. This is of course a crucial issue, as we cannot claim to understand bars fully if we can not explain how they formed. It is interesting to note that barred spirals are almost absent at the highest redshifts observable (see van den Bergh et al. 1996 for the Hubble Deep Field), while they are present in large numbers at intermediate redshifts (Couch, private communication), and dominate locally (e.g. Sellwood & Wilkinson 1993). It would be extremely interesting to determine when and in what environment bars can form. Both goals can be achieved by comparing the fraction of barred spirals in the field and in clusters as a function of redshift. With the advent of 8 m telescopes, such projects are now feasible, and they fit in very well with some of the major scientific objectives of this new generation of telescopes.

6.3.2 Dwarf and Elliptical Galaxies

The latest galaxies which are still clearly rotationally supported, the Magellanic irregulars, often have a bar which is offset from the center of the apparent disk (both photometrically and kinematically). Little is known about the dynamics of these systems, not even how the bar pattern revolves around the center of the disk (see, e.g., Colin & Athanassoula 1989; Odewahn 1994). Even less is known about their vertical structure. N-body simulations of rotationally supported disks, such as those of Combes et al. (1990), are representative mostly of early-type spirals. Similarly, our observations in Chapter 5 did not extend to spirals of type later than about Sc. It would thus be rewarding to search for bars in edge-on Magellanic irregulars. Any information gained this way would be an addition to our knowledge of these objects. As far as we know, no systematic study of their vertical structure has ever been attempted. However, it may be that the diagnostics developed in Chapter 3 and 4 are not appropriate for Magellanic irregulars, depending on the actual dynamics of the bars. In any case, a full study of the dynamics of these objects is warranted. Given the unusual location of the bar, such studies should prove very interesting and challenging.

The brightest elliptical galaxies are very likely to be triaxial systems (see, e.g., Binney 1980). Their figure is usually assumed to be non-rotating, but this may well be incorrect; there is little observational evidence to support this assumption. The results presented in Chapter 2 also suggest that the process of building up a dark halo may lead to a significant number of triaxial halos with a slow figure rotation. If this is true, then it seems likely that many elliptical galaxies would have a slowly rotating figure. It is possible that the bar diagnostics which we have developed for edge-on spirals could be applied to some ellipticals. Their figure rotation is likely to be slow, so the potentials should allow ILRs. As a small number of elliptical galaxies possess a significant gaseous disk, the effect of the resonances on the disks should be easily detectable, in a manner similar to the diagnostics presented in Chapters 3 and 4 (see also Bureau & Freeman 1997b). Another possible approach is provided by Tremaine & Weinberg's (1984) method. Although the method is designed to measure the pattern speed of 2D disks, none of the basic assumptions forbid an extension to 3D. It would thus be worthwhile to investigate if the method can be generalised to measure the pattern speed of triaxial ellipsoids. Elliptical galaxies with a minor axis dust lane may prove important for such studies, as in these objects the orientation of the line of nodes on the sky is known.

The simulation results presented in Chapter 2, which suggest that dark matter halos are not only triaxial but also have slowly rotating figures, were taken from a set of low resolution cosmological structure formation simulations constructed for a different purpose. We believe studies of figure rotation in halos should be extended to a larger range of simulations. In particular, it would be interesting to see if, in higher resolution simulations, halos with scales comparable to those of elliptical galaxies continue to display figure rotation.

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