CHAPTER 1

Introduction

This thesis deals with two of the spheroidal components of spiral galaxies: The bulge and the dark halo—their structure and relevance to the process of galaxy formation. In this Introduction we try to define these two entities, give a brief overview of the relevant research and describe their status in the picture that astronomers have for spiral galaxies. At the end of each Section, we give a brief outline of the relevant chapter(s) of this thesis.

1 Bulges of spirals

1.1 Overview

bulge, *n.* — A swelling *(Roget's Dictionary)*

Looking at the picture of the edge-on spiral NGC 4565 on the following page, one can distinguish, at first glance, two major components: the disk and the bulge. The disk, in this case, is outlined by the very prominent dust lanes that cause the dark rift along the edge of the galaxy. The bulge—so named because, simply, it bulges out of the disk—is the smooth spheroidal system in the center. In the past, this structure was often referred to as 'the nucleus' (e.g. Hubble 1936); this term has now come to describe the very central region of the bulge. It has also been called 'the spheroid'. This otherwise elegant word was used when the bulge was thought to be just the inward continuation of the luminous stellar halo and the term 'spheroid' included both of these systems. This term is now largely abandoned, once the significant differences between the bulge and the halo were realized.

Although it can be misleading and often counter-productive, it is nevertheless useful to give a working definition for the system under study. One can define the bulge as a flattened spheroidal system of stars in the center of spiral galaxies*. Typically this should also include the interstellar matter (ISM) enclosed in this region, but this is usually assigned to the disk; in this thesis the ISM in the bulge is not dealt with. The total luminosity

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*The absence of any reference to age, metallicity or kinematics of the bulge stars in this definition is deliberate—the existence of a separate "bulge" or "nucleus" was acknowledged long before anything was known about these parameters, and was almost entirely based on geometry.

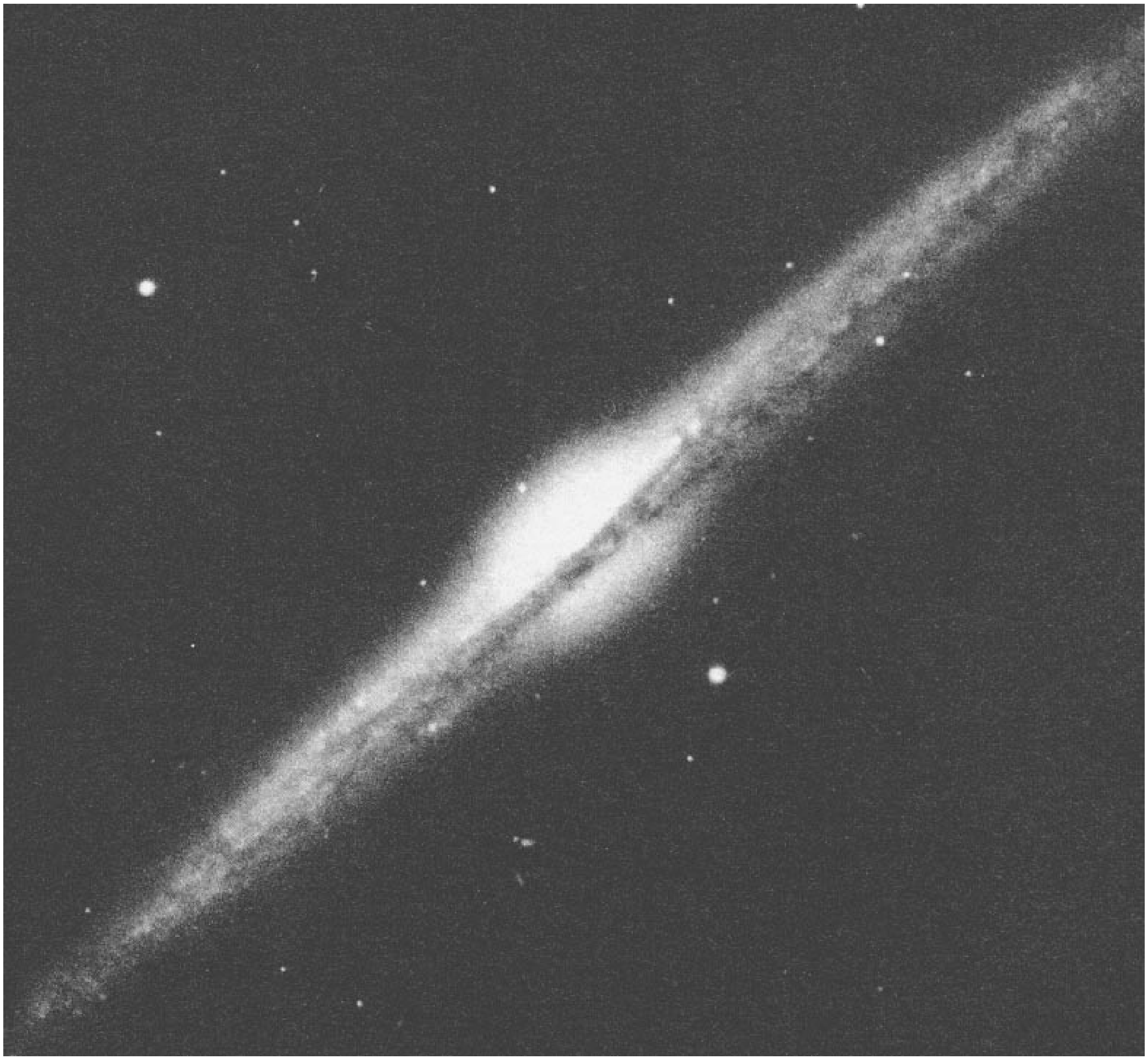

Figure 1: The Sb spiral NGC 4565 from the *Hubble Atlas of Galaxies*. The bulge, despite its small size, is very prominent in the center of the disk.

of the bulge varies greatly from galaxy to galaxy, ranging from a few percent of that of the disk that surrounds it, up to 2 or 3 times the luminosity of the disk. This so-called bulge-to-disk ratio along with a few other criteria, are the basis of the galaxy classification scheme devised by E. Hubble and described in his book *The Realm of the Nebulae.*

Why are we interested in the bulge? It is a major—sometimes even dominant—component of spiral galaxies. The study of the bulge can give important evidence on the formation and evolution of these objects, or, in other words, about the past, present and future of one of the basic building blocks of the Universe. The reasons for this will hopefully become obvious in the next few paragraphs.

Bulges are, by definition, dense and bright objects, and at first one would assume that their study would be an easy task. But because they are surrounded by stellar and gaseous—and in many cases heavily obscuring—disks, the task is more difficult than expected. The rather frustrating result is that after more than 50 years of observations some fundamental questions still remain unanswered. Following Ivan King in his review talk at IAU Symp. 153, there are four general questions that we can ask about the bulge, or, for that matter, about any stellar system: What is there, how it moves, how it is distributed and how it got that way. We will briefly address each one in turn.

Based on studies of the bulge of the Milky Way and those of nearby galaxies such as M31, it is believed that today we have a pretty good idea of the stellar populations that comprise the bulk of the stars in bulges. The question was first addressed by Baade (1944) in his classical study where he introduced the concept of Stellar Populations. By observing red giants in the bulge of M31 he concluded that it consists mainly of old and metal poor stars, much like the ones in the halo and the halo globular clusters. This picture, despite being called 'classical' some times, was not entirely correct. Thirteen years later Morgan & Mayall (1957) found that the spectra of bulges were like those of solar type stars; Spinrad (1966) even spoke about super-metal rich bulges. The current ideas about populations and metallicity (Rich 1992, Minniti et al. 1995, Jablonka et al. 1996) actually include all of the above; the bulge stars have a very wide range in metallicity and the main population tracers in regions like Baade's window are K and M giants, OH/IR stars and Mira variables. Up to now, firm age limits have been found for the bulge of the Milky Way (Ortolani et al. 1994) and M31 (Jablonka 1997). The stars in these bulges were found to be about 10 Gyrs old; at least for these two galaxies, the bulge is among the oldest components. As far as the stellar kinematics are concerned, bulges as a rule are fast rotators and the very few relevant studies (Kormendy & Illingworth 1982, Kent 1992) show that in general they are consistent with models of isotropic oblate spheroids.

Regarding the distribution of stars in the bulge, with the exception of the Milky Way, we can only measure the bulge projected density, or surface brightness. To do this reliably, one must be able to isolate the bulge light from that of the disk, a process that is known as bulge-disk decomposition. But because we don't know beforehand the light distributions of these two components *at all radii*, the problem is often degenerate. This means simply that the total light profile of the galaxy can be satisfactorily described by the sum of more than one pair of functions for the bulge + disk system.

The first attempt to decompose bulge and disk was made by G. de Vaucouleurs (1958) for M31. Figure 2 is a reproduction from the original publication of the procedure he followed. He assumed that the disk surface brightness is constant inside the central 30' and subtracted this constant value from the total light profile to retrieve the bulge light. The resulting profile followed the $r^{1/4}$ law which de Vaucouleurs had found to describe the profiles of elliptical galaxies (de Vaucouleurs 1948). Since then, modeling of the bulge as an $r^{1/4}$ spheroid became standard practice (Kormendy 1977, Boroson 1981, Simien & de Vaucouleurs 1986). This view of the bulge morphology, a very old, $r^{1/4}$ oblate spheroid similar to elliptical galaxies dominated until the early 80's and was consistent with the then dominant galaxy formation theory, the ELS scenario (Eggen, Lynden-Bell & Sandage

1962). This brings us to the last of the questions posed previously, namely the formation mechanism of the bulge.

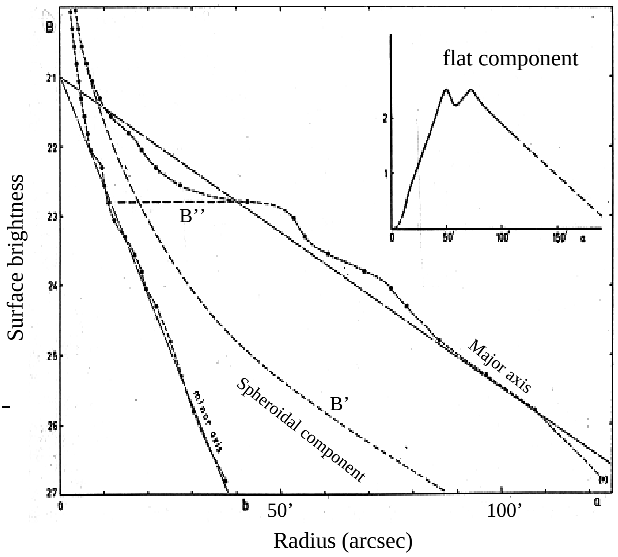

Figure 2: The original bulge-disk decomposition by G. de Vaucouleurs, with some of the labels redrawn for clarity. The flat part B" was taken to represent the disk in the central 30'. The inset plot shows the remaining disk after subtraction of the $r^{1/4}$ bulge.

This is the subject on which we know the least; at the same time it is also the most important, since it is essentially another way of posing the question of how galaxies formed. According to ELS, galaxies formed from the rapid monolithic collapse of an overdensity region in the expanding Universe. The lowest angular momentum gas fell into the center and formed the bulge; fast star formation and subsequent enrichment can explain the bulge metallicity. The high angular momentum gas collapsed *later* and formed the disk. In this scenario, the bulge is essentially the oldest component of a spiral galaxy; within this context, it is called the 'old-bulge' scenario. The ideas of Searle & Zinn (1978) and Toomre (1977) about chaotic collapse of protogalactic fragments and the importance of mergers respectively, showed that there are more ways to build galaxies, other than monolithic dissipational collapse. Observations of the stellar kinematics and metallicity of the Milky Way halo suggest that at least a part of it has probably formed by accretion of sub-galactic units (Majewski 1992, Carney 1993). It has also been shown that elliptical galaxies can be formed by merging of two spirals (Barnes 1988). These facts gave rise to modern galaxy formation scenarios, such as those of Kauffmann et al. (1993) and Baugh et al. (1996), where galaxies are formed via hierarchical merging of dark halos, and their morphology is determined by the availability of gas that can form a disk. Within these scenarios, the bulge is again formed early in the history of the galaxy by merging of two stellar disks, and is in effect a disk-equipped elliptical galaxy.

These 'early bulge' scenarios are opposed by some radically different ideas developed in the early '80's, prompted by the results of N-body simulations. Combes & Sanders (1981) first demonstrated that the vertical thickening of a stellar bar can produce a bulge-like object in the center of the disk. This conclusion was later confirmed and refined by Hasan, Pfenniger & Norman (1993) and this mechanism is now established as a plausible bulge formation scenario[†]. In general, however, the bulges produced by this mechanism are small compared to the disk; multiple minor accretion events were proposed as a possible mechanism to account for the formation of the big bulges of early type spirals.

At around the same time, the first indications of bulges having characteristics unac-

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[†] This scenario is often called the 'secular evolution' origin of bulges, or 'late bulge'.

counted for by the 'old bulge' picture emerged. Not all bulges are oblate spheroids; a significant percentage (20-30%) (Shaw 1987) are box-or peanut-shaped and triaxiality has also been observed (Bertola et al. 1991). The deprojected density of some bulges, including that of the Milky Way is bar-like or triaxial (Dwek et al. 1995). Some bulges are not 'hot' systems but 'cold', with velocity dispersions being closer to those of disks (Kormendy 1992). A number of bulges have colors similar to disks (Balcells & Peletier 1994) and sometimes spiral structure, traditionally attributed to the disk, continues well into the bulge (Kormendy 1992). Finally, it was realized that not all bulges follow the $r^{1/4}$ law in their light profile. The bulge of the Milky Way has an exponential profile outside 300 pc (Frogel 1988, Kent, Dame & Fazio 1991); the bulge of NGC 4565 (Fig. 1) is also exponential (Frankston & Schild 1976) and deviations from the $r^{1/4}$ profile have been observed in other galaxies (e.g. Wainscoat et al. 1989). Slowly, the idea emerged that perhaps not all bulges had formed in the same way and that some, or even most bulges have formed *after* the disk, by those dynamical processes found in N-body simulations, such as bar thickening or accretion. The correlation between bulge and disk scalelengths found recently (Courteau et al. 1996) was also interpreted in the same light. The final result is the existence of two conflicting theories about bulge formation: 'early' and 'late'.

This circle from the bulge surface brightness distribution to galaxy formation scenarios and then back again to the bulge surface brightness serves to show the degree to which these subjects are connected. We want to understand how galaxies formed; a key question related to this is the bulge formation epoch and mechanism. *The objective of this thesis is to find clues about the origin and the formation epoch of the bulge through a consistent description of the surface brightness profile and the analysis of any systematic trends therein.*

For this purpose, different decomposition methods are employed, using both optical and near-infrared data. The results allow some conclusions to be drawn regarding the formation epoch of the bulge, and these conclusions are subsequently evaluated through the use of N-body simulations.

1.2 Observations and analysis of bulge surface brightness distribution: Outline

In Chapter 2, optical surface brightness data from the literature are used to decide whether the bulges of late-type spirals are better described by an exponential instead of an $r^{1/4}$ law. The classical decomposition method of fitting bulge and disk models simultaneously to the profile of the whole galaxy is used. For the first time the effects of seeing are taken into account in this procedure, by convolving the function used to describe the bulge with a Gaussian Point Spread Function of the appropriate width. The uncertainties in the best-fitting model caused by the seeing are also considered by analyzing artificial profiles. Finally, the distributions and correlations of the bulge and disk parameters for each bulge model are examined.

In Chapter 3 the bulges of a sample of 30 early type spirals are considered, using new near-infrared (K-band) data. The significant reduction of dust extinction, along with a new 2-dimensional decomposition method that does not assume *a priori* certain surface brightness laws for the bulge and disk, allows a much more detailed and reliable analysis. The uncertainties introduced by the sky subtraction, the limiting magnitude and the decomposition method itself are examined carefully using artificial 2-D galaxy images. The bulge profiles are described using Sersic's law; the use of this 3-parameter function allows the shape of the light profile to be quantified, and some rather strong trends to be detected.

Finally, in Chapter 4, collisionless numerical simulations are used in an effort to reproduce the trends observed in the analysis of Chapter 3. The simulations follow the classical picture of bulge formation—a disk is grown slowly around an already formed bulge. This produces some easily detectable effects on the bulge, which are then compared to the results of Chapter 3. The conclusions of this and the previous chapters will be presented in the Summary of this thesis.

2 Dark matter halos of spirals

The idea that the Universe contains large quantities of dark matter—matter that does not radiate in the observable electromagnetic spectrum—is very old and still remains perhaps the most intriguing problem in Astronomy. In fact, at the time of writing of this thesis, and according to the earliest documents that the author could find, the idea of spheroidal dark matter halos around galaxies is exactly one century old. Based on proper motion measurements of nearby stars, Newcomb (1897) suggested that if those are not runaway stars, then there must be much more mass in the Universe than we can observe. D'Auria (1897) postulated the existence of "a sphere of ether [...] that attracts matter by gravity [...] containing all the stars of the visible Universe" to explain these proper motions[‡]. The first really influential evidence was found by Zwicky (1933), who calculated the total mass of the Coma cluster by applying the virial theorem using the measured radial velocities of the galaxies. Comparing the resulting total mass-to-light (M/L) ratio to the M/L observed in nearby galaxies he found a discrepancy of the order of 50, in the sense that within the cluster there was 50 times more mass than that which could be accounted for by the luminous matter in galaxies. The problem remained at that point until the beginning of the '70s, when Ostriker & Peebles (1973) showed that the existence of a massive spheroidal dark halo was necessary in order to stabilize the stellar disk against bar formation. At around the same time the first extended (single-dish) 21-cm rotation curves became available, and Freeman (1970) pointed out that the rotation curves of M33 and NGC300 did not decline beyond the end of the luminous matter; this implied the existence of a roughly spherical dark matter halo encompassing the galaxy, with a total mass at least as large as that of the visible galaxy. Analogous results were obtained by optical rotation curves (Rubin & Ford 1970), although those were later explained without the need for dark matter (Kalnajs 1983). The modern track was set by the first H I synthesis observations of a sample of spirals by Bosma (1978) and continued by Begeman (1987) and Broeils (1992);

[‡] The 'ether' mentioned here is the elusive medium through which electromagnetic radiation was thought to propagate, and which was supposed to pervade all space—for the time, a very good dark matter candidate indeed! The 'Universe' of 1897 was what we would call today the Milky Way galaxy; the existence of external galaxies was not acknowledged until 25 years later.

it was found that the majority of the rotation curves of spirals do not show the expected Keplerian decline beyond the edge of the visible galaxy but are flat out to the furthermost measured point. This result made it clear that, assuming Newtonian dynamics, a dark matter halo is necessary to explain the rotation curves of spiral galaxies. The high-quality data made it also possible to fit the observed rotation curves using mass models for the various luminous components of the galaxies (bulge, stellar disk, gaseous disk) and hence to draw conclusions about the distribution of the dark matter (van Albada et al. 1985). The dark halo was successfully modeled as an isothermal sphere, whose total mass and core radius could be adjusted to fit the observations.

In the meantime, simple analytical models were developed for the collapse of density peaks in the early Universe that would eventually lead to the formation of galaxies (White & Rees 1978). In these models the luminous (baryonic) matter is initially uniformly mixed with the dissipationless dark matter, and a given density peak (a seed for galaxy formation) is slowly rotating due to external tidal torques. The baryonic matter eventually dissipates its energy and collapses to the center ('baryonic infall') where it spins up and forms the visible galaxy. Note that there are two distinct events in this procedure: the gravitational collapse and virialization of the density peak that includes *all* the mass of the galaxy and essentially forms the dark halo; and the subsequent collapse of the dissipational matter to the center[§]. In the last few years the halo formation has been simulated numerically with a high resolution (Dubinski & Carlberg 1991, Navarro et al. 1996). The initial conditions used in these simulations are those of the Cold Dark Matter initial fluctuation spectrum (Blumenthal et al. 1984) that successfully predicts the observed large scale distribution of matter. The halos resulting from the simulations, however, have a steep density gradient at the center (with a singularity at r=0) instead of the constant density core needed to explain the H I rotation curves. In principle it is possible to fit the rotation curves of luminous spirals using these halos (Sanders & Begeman 1994), but this is not possible for the dark matter dominated dwarf galaxies and Low Surface Brightness spirals (de Blok 1997). In addition to that, the second infall event—the baryonic infall—would certainly change the halo structure and introduce further complications.

Chapter 5 of this thesis deals exactly with this last question. We simulate the formation of an exponential disk inside a singular halo, and study the effects that this has on the shape and mass distribution of the halo, and on the final rotation curve of the galaxy. The results allow us to draw conclusions about the plausibility of the proposed initial halo density laws—and indeed are relevant to the plausibility of the CDM model itself.

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[§] We distinguish these events here for the sake of clarity—this does not exclude them from overlapping in time.

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