

CHAPTER 6

Summary

1 Bulges of spirals: Light profile and evolutionary history

In this thesis, two problems have been addressed: The description of the surface brightness profile of bulges, and, through that, the place of the bulge in the evolutionary history of spiral galaxies.

In Chapter 2 the surface brightness profiles of 30 late type spirals are decomposed into bulge and disk. The classical decomposition method is used, of simultaneously fitting the sum of two functions to the light profile; the difference between this and previous attempts is the use of a seeing-convolved function for the bulge. Two different functions are used for the radial dependence of the bulge surface brightness, the standard de Vaucouleurs' (or $r^{1/4}$) law, $\Sigma(r) \propto \exp[-k(r/r_0)^{1/4}]$ and a simple exponential law, $\Sigma(r) \propto \exp[-k(r/r_0)]$. The degeneracy of the problem, i.e. the fact that the unique sum of a disk and a bulge profile can under certain conditions be equally well fitted by either model, is carefully taken into consideration by analyzing artificial profiles and confidence limits are established. By the fits it is found that for most of the galaxies, and especially for the ones with the smallest bulges, the exponential function for the bulge gives a better fit to the data. More important is the fact that with the exponential model the parameters of the bulge like effective surface brightness and radius, span a much narrower range of values than with the $r^{1/4}$ law. Moreover, the correlations of the bulge parameters among themselves and with those of the disk are much clearer.

In Chapter 3 a new bulge-disk decomposition method is developed, that uses the entire 2-dimensional image of the galaxy and makes no assumption about the surface brightness law that the bulge and disk follow. It is applied on a sample of 30 early type spirals observed in the near infrared K band. The effects of sky subtraction, limiting magnitude and the errors introduced by the decomposition method are again considered in detail by analyzing artificial images. After decomposition, the bulge profiles are fitted using Sersic's law, $\Sigma(r) \propto \exp[-k(r/r_0)^{1/n}]$ where $n = 4$ gives the de Vaucouleur's law, and $n=1$ gives a pure exponential; this allows the *shape* of the light profile to be quantified, through the parameter n . The final best-fit n 's range from around 1 up to 6, and they show a rather

strong correlation with the morphological type of the galaxy and the bulge to disk ratio. Early type spirals and S0's with a large B/D ratio have bulges with profiles close to the de Vaucouleur's law, while the bulges of Sa and Sb galaxies are better described by an "r-to-the-half" law ($n = 2$). The bulges of even later types with the smallest B/D ratios are close to exponential, in agreement with the results of Chapter 2. This correlation of n with B/D ratio is most easily interpreted as an effect of the disk on the bulge. Furthermore, the continuity in the spectrum of n might indicate that all bulges were formed by a common mechanism early in the life of a galaxy, and their properties were later systematically modified by the formation of the disk.

In Chapter 4 the hypotheses of Chapter 3 are tested by numerical simulations. The initial bulge is represented by an N-body sphere in equilibrium that follows an $r^{1/4}$ law. The potential of an exponential disk is then adiabatically grown in and around the bulge; various masses and scalelengths of the disk are used, in order to cover the parameter space of bulge to disk mass and scalelength ratio of real galaxies. When the formation of the disk is complete, it is found that the best-fit n (of the Sersic law) has decreased indeed from the initial value of 4 to smaller values, depending on the mass and scalelength of the disk: More massive and more compact disks give a smaller n , in general agreement with the results of Chapter 3. A large part of the observed correlation of n with B/D ratio is reproduced, as well as the exact shape of a number of the observed profiles. The same result holds for the observed correlation of disk scalelength with bulge effective radius. This correlation has been used to support the "secular evolution" scenario for bulge formation (see the Introduction for details). In the simulations of this chapter the greatest part of this trend is reproduced; it arises naturally if the bulge was formed before the disk, and was later forced to a smaller size by the disk potential. The exponential bulges ($n = 1$), however, cannot be produced by this mechanism; the induced decrease in n saturates at around $n = 2$.

There are two main conclusions that we can draw from this work. First, the shape of the surface brightness profile of bulges changes systematically with morphological type. At least outside the resolution limit imposed by seeing effects, the bulges of early type spirals follow in general the $r^{1/4}$ law; as we move to later type galaxies the profiles are described by lower- n Sersic laws that fall off more steeply with radius in the outer parts than $r^{1/4}$. This result has now been confirmed by a number of authors, both photometrically, using 2-dimensional fitting techniques (de Jong 1995, Courteau et al. 1996) as well as dynamically, through the bulge mass models required to fit the inner parts of rotation curves of spirals (Heraudeau et al. 1997).

Second, the fact that this trend of the shape of the light profile is reproduced by simulations where the bulge was formed before the disk, suggests that at least the bulges of spirals as late as Sb were already in place when the disk started forming. Note that this result does not necessarily falsify the possible late bulge formation via mergers or secular evolution, but, along with the most recent age determinations, it provides strong support to the opposite, "old" bulge scenario. The situation for the late type galaxies is not yet clear. Given that the exponential shape cannot be attributed to the disk formation, and that in these bulges phenomena such as 'peanut' shape, disk-like velocity dispersions and disk-like colors are most often observed, we can say that the secular evolution origin—such

as, for example, vertical thickening of a bar—seems quite probable. A bar seen end-on has, indeed, an exponential surface brightness profile. Perhaps late-type galaxies with a small initial bulge to disk ratio are more susceptible to bar formation and subsequent growth of an exponential bulge.

We are now in a position to place the bulge in the galaxy formation and evolution picture with a little more confidence: Bulges of early type spirals, were most probably formed early in the life of the galaxy, either by collapse of the low angular momentum gas in the halo to the center, or by hierarchical merging of subclumps, as indicated for example by the latest HST results (Trager et al. 1997). Whatever the formation mechanism, the disk was formed *afterwards*, and this process left its imprint on the bulge, in the systematic change of the light profile that we observe today. In the late type spirals, the bulges that we observe probably formed, at least in part, by other mechanisms; various candidates so far are bar thickening and/or destruction, thickened disks, or bars themselves.

2 Dark halos of spirals: Initial density laws

In the last part of this thesis, we have considered baryonic infall inside a dark matter halo. Our purpose is to study the effects that this has on the halo density distribution and on the final form of the galaxy rotation curve. The ultimate goal is to put constraints on the possible initial density distribution of the halo by comparing our results with observed rotation curves.

Two models are used to represent the dark halos in this study. The first one is the Hernquist model, with a density that rises steeply in the center as r^{-1} . This model is a good representation of the halos that form from the collapse of density peaks in the Hubble flow, with Cold Dark Matter (CDM) initial conditions. The second model is the γ_0 model of Dehnen, that has a constant density core. The baryonic infall is simulated as in Chapter 4, by slowly turning on the potential of a thin exponential disk inside the N-body halo. The halo reacts to the baryonic infall by contracting and flattening slightly. This contraction causes the initial central density profile to become steeper, and this has some direct consequences for the plausibility of the initial halo density law: Using CDM (i.e. Hernquist) halos, the final (total) rotation curve of the galaxy does not have a flat part, as is observed in the majority of luminous spiral galaxies. For all the disk scalelength-mass combinations within the limits set by angular momentum constraints and nucleosynthesis arguments respectively, the final rotation curves are declining almost throughout the observable range of radii. The γ_0 halo can give the desired flat and featureless rotation curves; until this moment, however, only Hernquist-type halos are formed in cosmological CDM simulations (Moore et al. 1997, Navarro et al. 1996)

This incompatibility between CDM halos and observed rotation curves has been realized in the past for dwarf galaxies, whose rising rotation curves are in clear contrast to the form of these halos. Here we show that this extends also to the flat rotation curves of normal spirals. To explain flat rotation curves, halo models with a constant density core are needed; this might imply that alternative forms of dark matter need to be considered.

3 Outlook

The overall problem considered is galaxy formation; bulge or halo formation and evolution are just two pieces of this puzzle. At this moment there is a large influx of new data on high redshift galaxies from HST and the new 10m class telescopes that will undoubtedly shed new light on our understanding of galaxy evolution. The much needed HST data on the centers of bulges are being analyzed, and in this respect, research is already in a very promising track and new suggestions are redundant. However, as often happens in Astronomy, theoretical progress lags behind the experimental data. It is therefore the author's opinion that we need a better understanding of the combined effects of the various physical processes in galaxies, and this can be accomplished through large scale numerical simulations in the manner of Katz (1991) and Steinmetz & Muller (1995). These simulations are rapidly becoming faster and more sophisticated, and together with some—constantly in demand—radical new ideas that would prompt us to either review or strengthen the current theories, might lead to a greater understanding of the process of galaxy formation.

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