Mid-infrared imaging of dust in galaxies
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The assembly of bulges

For understanding the nature and formation of bulges it is important to understand their properties. If there are two kinds of bulges, named pseudobulges and classical bulges, there should be an easy and straightforward way to classify them. We have studied Spitzer colours, Sérsic indices, SAURON stellar kinematics, ionized gas emission and absorption line indices to define a classification method that can classify pseudobulges in the SAURON Sa sample on a physical basis. Our best method is a morphological classification where central components that have a similar flattening to that of the outer disc and/or irregular or bar-like isophotes in HST and 3.6 µm images are called pseudobulges, and objects with smooth, elliptical-like isophotes are classified as classical bulges. Using this definition 5/24 galaxies have a classical bulge, while 19/24 show a pseudobulge. Pseudobulges defined using our morphological classification do not necessarily coincide with the bulge that is obtained using photometric decomposition of a spiral into an exponential disc and a spherical bulge. With our method the pseudobulge is best described as a central disc component with dust, gas and often central star formation. These often coincide with central velocity dispersion dips. Of the bulges we classify morphologically as pseudobulges 70% have a $\sigma$-drop, indicating that $\sigma$-drops are a good tool to find pseudobulges. The stellar kinematics indicate that these bulges are assembled in a secular evolution process via bars, ovals or dynamical friction. The classical bulges are more likely the result of a major merger, a series of minor mergers and/or early dissipative collapse.
3.1 Introduction

Galactic bulges were originally thought to have $r^{1/4}$ surface brightness profiles (Kormendy & Illingworth 1982). Because of this and other similarities with elliptical galaxies, such as age and metallicity, these bulges were thought to be the product of early dissipative collapse (Eggen et al. 1962) and possibly mergers (Toomre 1977) around which later a disc with spiral arms forms. In the scenario of multiple minor mergers similar bulges can form (Combes 2009).

This picture had to be revised several times, as better observations became available. It was found that the surface brightness profiles are fitted better by Sérsic $r^{1/n}$ profiles, where $n$ gets smaller for later type galaxies (Andredakis et al. 1995). About the same time Kormendy (1993) found that many bulges have properties that are different from those of giant ellipticals: they rotate fast, have exponential surface brightness profiles, contain gas, dust and/or signs of recent star formation. He called these bulges pseudobulges. Objects resembling elliptical galaxies were called classical bulges.

Kormendy & Kennicutt (2004) hint that pseudobulges have had a different formation history, where the bulge is built from disc material via a so-called secular evolution process. In this process material is funnelled into the central regions, e.g. by bars. When the bulge becomes massive enough, the bar is destroyed, and the process starts again (Norman et al. 1996). In this way, one expects exponential bulge surface brightness profiles, the presence of cold/warm ISM, and young stars in the inner regions. Without spirals and bars, bulges can also form and even more quickly: simulations show that gas-rich discs will become clumpy and that these clumps will coalesce and produce pseudobulges through dynamical friction (Combes 2009). In the definition of Kormendy & Kennicutt (2004), a pseudobulge can also be characterized by one of the following properties: 1) the bulge looks like a disc and shows similar flattening as its outer disc, 2) it is or contains a nuclear bar (only visible in face-on galaxies), 3) it is box shaped (only visible in edge-on galaxies), 4) it is more rotation-dominated – with stellar velocity over velocity dispersion ratios ($V/\sigma > 1$) than a classical bulge, 5) has a lower mass-to-light ratio than elliptical galaxies as seen in $\sigma$-luminosity plots, and 6) is dominated by star formation, gas and dust, but shows no signs of a merger in progress.

With again better data being available, the SAURON spiral studies revealed through their stellar kinematic and population maps that many bulges contain a fast-rotating disc of young stars, including gas and dust, apart from a more slowly rotating, elliptical-like component (Ganda et al. 2006; Falcón-Barroso et al. 2006; Peletier et al. 2007; Peletier 2008). In some of these galaxies, the discs dominate the central light as seen in for example NGC 4274 (Fig. 3.1). The SAURON studies of elliptical and lenticular galaxies show that young stars are also present in the central regions of some fast-rotating systems (Kuntschner et al. 2006, 2010; Shapiro et al. 2010). In some of the galaxies this star formation is widespread across the central region, is associated with counterrotating components and is thus likely due to minor mergers. In other galaxies the star formation is concentrated into well-defined disc or ring morphologies, outside of which the host galaxies exhibit uniformly evolved
stellar populations. This and the ubiquitous presence of corotating inner stellar discs implies that these star formation events are due to secular evolution.

Given the problems in implementing the definition of Kormendy & Kennicutt (2004), Fisher & Drory (2010) recently introduced a new definition. They show that the Spitzer [3.6]−[8.0] colour index, a star formation tracer, can also be used to identify pseudobulges: none of the bulges with elliptical-type morphology has a mid-infrared colour [3.6]−[8.0] > 1.9 mag in the VEGA magnitude system. When star formation does take place ([3.6]−[8.0] > 1.9 mag) in a bulge it always has a disc-like morphology. However, bulges with such a morphology do show a large range in colour: pseudobulges can be both active and inactive at forming stars. These inactive pseudobulges are likely composite systems, in which both a pseudobulge and classical bulge exist with about equal mass ratio. From 3.6 µm surface brightness profile fitting they find that the vast majority of disc-like bulges have a Sérsic index less than $n = 2$, and that all elliptical-type bulges have a Sérsic index that is greater than 2. This is similar to what is found in the optical V-band.

For understanding the nature and formation of bulges it is important to know whether the abovementioned classification scheme is adequate. Here we use some additional diagnostic indicators, the SAURON stellar kinematics, ionized gas emission and absorption line indices to see whether a better scheme is possible.
### 3.2 Classifying bulges

How can we recognize pseudobulges and classical bulges? We start classifying our bulges in the SAURON Sa sample (see Chapter 2) via the curvature of the galaxy’s radial photometric profile – this is known as Sérsic index – and the presence of star formation in the bulge as measured with mid-infrared colour ([3.6]−[8.0] or [8.0]−[24]). Fisher & Drory (2010) show that these two diagnostics are related to the bulge morphology as seen in HST images, being either elliptical (smooth isophotes with little-to-no substructure) or disc-like (spiral structure, rings and/or bars). We determine photometric profiles, bulge mid-infrared colours, and bulge morphology for the galaxies in our sample and formulate our own definition for pseudo and classical bulges.

We compare our findings with Fisher & Drory (2010) who study 146 nearby (< 20 Mpc) and low-to-moderately inclined (i < 70) RC3 disc galaxies, which are free of interaction events, such as tidal tails, warps and asymmetries in the 3.6 μm images. Of these galaxies 27 are of Sa type. This makes their sample a good comparison sample. There is overlap with the SAURON Sa sample, 4 galaxies (NGC 4274, 4293, 4314 and 4698) are included in their sample. According to their distance and inclination...
3.2 Classifying bulges

Figure 3.2: Bulge classification using mid-infrared colour of the bulge shown in a diagram of Sérsic index versus Spitzer colour (left). On the right the total colour is plotted. We use the definition that a galaxy is hosting a pseudobulge if its bulge light has a colour $[3.6]−[8.0] > 1.9$ mag or $[8.0]−[24] > 2.0$ mag (vertical) or a Sérsic index of $n_{3.6} < 2.0$ (horizontal). In the top-left boxes both classifications (P=pseudobulge; C=classical) are coded: first using Sérsic index, and then using colour. In yellow we plot galaxies that we identify as AGN using the $[3.6]−[4.5]$ colour (Chapter 2).

selection criteria their sample should include 7 more SAURON Sa galaxies (NGC 4220, 4245, 4383, 4405, 4425, 4596 and 4772). NGC 4383 has probably been removed from their sample due to its RC3 classification as peculiar. None of these galaxies host an AGN. Possibly the data of some of these galaxies were not available at the time of their analysis: a few galaxies were observed in Spitzer Cycle 5 (NGC 4220, 4425 and 4772).

Photometric profile classification

How do we determine Sérsic indices and what do they tell? We determine the curvature of the radial profiles, known as Sér...
Sérsic indices, \( n_V \) and \( n_{3.6} \), are listed in Table 3.1 together with literature values found for a few of the galaxies (Fisher & Drory 2010). When we define a bulge to be a pseudobulge when \( n \leq 2 \) (Kormendy & Kennicutt 2004) with \( n_{3.6} \) our sample contains only 5 pseudobulges and 7 with \( n_V \): the differences between \( n_{3.6} \) and \( n_V \) are small. Only NGC 2273 has a much higher \( n_{3.6} \) than \( n_V \), which must be due to the active nucleus. In the following analysis we make use of the \( n_{3.6} \) Sérsic index, since the 3.6 \( \mu \)m images are not affected by extinction. Compared to the literature values our \( n_{3.6} \) values match with those of Fisher & Drory (2010).

**Infrared colour classification**

Is star formation a better pseudobulge indicator than the curvature of the radial profiles? From the definition of Sérsic index \( n_{3.6} < 2 \), only 5 of the galaxies harbour a pseudobulge. In Fig. 3.2 we investigate how this classification relates to star formation. Using the definition from Fisher & Drory (2010) that galaxies with \([3.6]−[8.0] > 1.9\) mag (VEGA) have significant star formation, we see that just as many galaxy bulges in our sample host star formation as there are bulges without much star formation. Of the 5 galaxies that are classified as pseudobulges from their Sérsic index only 2 show significant star formation. In Chapter 2 we have seen that the \([8.0]−[24] \) colour is a better star formation tracer than \([3.6]−[8.0] \), and that in this colour more bulges seem to host star formation. NGC 5475 for instance has \([3.6]−[8.0] < 1.0\) mag, and a \([8.0]−[24] \) colour larger than 2.0 mag. All the galaxies with a \([8.0]−[24] \) bulge colour less than 2.0 mag have \([3.6]−[8.0] < 1.0\) mag suggesting that the definition from Fisher & Drory (2010) for pseudobulges should be lowered by 0.9 mag.

Why do so many bulges in our sample (8/10) with star formation show high Sérsic indices? In the sample of Fisher & Drory (2010) only 10% (6/53) of bulges with \([3.6]−[8.0] > 1.9\) mag have a Sérsic index \( n_{3.6} > 2 \), also when considering their subsample of Sa galaxies (1/12). The one galaxy of Sa type is also included in our sample (NGC 4314). The differences between our and their sample are not due to inclination. All of the galaxies with SF and excess \( n_{3.6} \) Sérsic index in our sample are low-to-moderately inclined (\( i < 70 \)). The distance of these galaxies does differ a bit: our sample has a median distance of 22 Mpc, and the sample of Fisher & Drory (2010) does not include galaxies with \( d > 20 \) Mpc. One of the galaxies in our sample with SF and excess \( n_{3.6} \) Sérsic index (NGC 5953) does show an interaction event and would therefore not be included in the sample of Fisher & Drory (2010). And NGC 4383 would not be included due to its peculiar morphology: it has a starburst-like biconic outflow. The high Sérsic index of this galaxy might not be related to its starburst. The sample of Fisher & Drory (2010) includes galaxies with redder \([3.6]−[8.0] \) bulge colours (\( > 3.5 \) mag), which all have low Sérsic indices (\( n_{3.6} < 2 \)). This makes distance the only explanation for the higher frequency of Sa bulges in our sample with star formation and high Sérsic indices. It is, however, unsatisfactory, since the average distance of both samples is only different by 10 Mpc. A possible explanation for the high Sérsic indices could be the clumpy and ring-like nature of the star formation in and around these bulges contributing to the 3.6 \( \mu \)m emission.
Can we classify bulges morphologically, i.e. purely based on their images? We investigate our galaxy bulges by eye and distinguish between bulges that have an elliptical-like morphology and those that look like a disc. This was done using HST images, in the F606W filter if available, retrieved from the Hubble Legacy Archive[^1] and in

[^1]: [url: http://hla.stsci.edu]
two cases from the MDM images in Falcón-Barroso et al. (2006). We displayed the maps in logarithmic scale and chose a range of intensities that highlights the bulge light. We cross-checked our results with our 3.6 µm images with an overlay of V-band SAURON images (Fig. 2.27–2.49) and found similar classifications. We identify pseudobulges as having similar flattening to that of the outer disc and/or having irregular or bar-like isophotes. This is somewhat different from the definition by Kormendy & Kennicutt (2004); Fisher & Drory (2010), who define disc-like morphology from the presence of nuclear spirals, small bars, nuclear rings, and irregular patchiness. None of these features are for instance present in the central regions of the galaxies NGC 4425 and 5689, but their bulges do show similar flattening as their discs. We identify classical bulges like Fisher & Drory (2010) as having smooth elliptical-like isophotes. The results are shown in Fig. 3.3.

Four of the galaxies of which the bulge is morphologically classified as a classical bulge have a Sérsic index larger than $n_{3.6} > 3$ and a [3.6]–[8.0] colour $< 1.0$ mag and reside in galaxies that lack overall star formation. The bulge of the face-on ring galaxy NGC 7742 also has an elliptical-like morphology, and has a Sérsic index and [3.6]–[8.0] colour just at the limits defined by Fisher & Drory (2010) between pseudo and classical bulges, and does show star formation in the disc. The face-on orientation of this galaxy makes it difficult to determine the bulge morphology, but a nuclear light excess with smooth isophotes is clearly visible in comparison with the other face-on galaxies. The frequency of elliptical-type bulges in the Sa galaxies in the sample of Fisher & Drory (2010) is slightly higher 35 % (6/17) than the 20 % (5/24) in our sample. Of these elliptical-type bulges in their sample 80 % (5/6) have colours [3.6]–[8.0] $< 1.2$ mag like the elliptical-like bulges in our sample. The galaxy with [3.6]–[8.0] =1.5 mag has a Sérsic index of $n_{3.6} \sim 2$ is a face-on galaxy similarly as NGC 7742 in our sample. Four out of six elliptical-type bulges have $n_{3.6} > 3$ and two have $n_{3.6} \sim 2$. When we examine the HST maps of these galaxies with $n_{3.6} \sim 2$ (NGC 1617 and 7217) an E-type morphology classification seems debatable. With the strict selection criteria of [3.6]–[8.0] $< 1.2$ mag and $n_{3.6} > 3$ we find an E-type fraction of 20 % in both our (4/24) and the Fisher & Drory (2010) sample (4/27) of Sa galaxies. Of the 146 RC3 disc galaxies in the latter sample, 14 galaxy bulges can be classified with these two criteria as very likely being of E-type. Of these 14 galaxies, 6 are S0’s, 4 are Sa’s and 4 are Sb’s. This makes the fraction of E-type bulges in Sb galaxies 10 % (4/35), half the fraction of E-type bulges in Sa’s.

A new definition for bulge classification

The best way to distinguish between pseudobulges and classical bulges seems to be by investigating by eye if the bulge is flattened like its disc or not. Using this morphological classification we conclude that pseudobulges can also be identified via radial profiles with curvatures $n_{3.6} \leq 2$, but that galaxies with a higher Sérsic index can host pseudobulges as well. Pseudobulges can also be identified using star formation. Our sample suggests that all bulges with colours [3.6]–[8.0] $> 1.0$ mag or [8.0]–[24] $> 2.0$ mag are pseudobulges. Note that NGC 7742 is an exception being a classical bulge surrounded by a star formation ring. Not all bulges below these mid-
3.3 Bulge classification versus SAURON data

Infrared colour limits are classical using the definition of Sérsic index ($n_{3.6} > 2$). This morphological classification thus entails a new definition for classical bulges as having $[3.6] - [8.0] < 1.0$ mag and $n_{3.6} > 3$. This would make the fraction of pseudobulges 80%. In 20% of these pseudobulges there is no trace of star formation.

3.3 Bulge classification versus SAURON data

How does our bulge classification correlate with SAURON properties? How do the SAURON star formation tracers correlate with Spitzer colours? Can the SAURON metallicity and stellar population age tell us more about the bulge formation history? Can the presence of σ-drops, kinematically defined discs (KDs) and kinematic misalignments – bars – tell us more about the bulge identification? And how does bulge classification relate to galaxy mass?

To compare our IRAC galaxy data with the absorption line strength, gas ionization, and gas and stellar kinematical data from SAURON (Falcón-Barroso et al. 2006; Peletier et al. 2007), we convolve the IRAC broadband images to the 2 arcsec resolution of the IRAC 8 µm image as in Chapter 2. Then we determine the fluxes of the Spitzer and SAURON data in a nuclear elliptical aperture with a radius of 3 arcsec along the major axis. The ellipticities and position angles are taken from optical RC3 data (Table 2.3). To study the characteristics of the various types of bulges we construct Spitzer colour versus SAURON data plots using the symbols for pseudo- and classical bulges determined by morphological classification (Fig. 3.3). We compare our data with the elliptical and lenticular SAURON galaxy sample SAURON and Spitzer data taken in apertures within one-eight of an effective radius $R_e/8$ and one $R_e$ (Shapiro et al. 2010; Kuntschner et al. 2010; Peletier et al. 2011).

3.3.1 Star formation

In the previous section we have seen that star formation in the bulge is strongly correlated with a disc-like morphology. Do the SAURON star formation tracers tell us the same story? We plot the $[3.6] - [8.0]$ colour against various gas emission (Fig. 3.4) and absorption line strengths (Fig. 3.5), with the aim of understanding which tracer can be used best to study the star formation in the bulges of our sample.

Emission lines

The SAURON study of the sources of ionization for the gas in elliptical and lenticular galaxies (Sarzi et al. 2010) indicates that the considerable range of values for the $[\text{OIII}]/\text{Hβ}$ emission line ratio both across the SAURON sample and within single galaxies can be attributed to one or more of the following: 1) a diffuse and old stellar population, 2) AGN, 3) shocks, 4) star formation, or 5) a post-starburst stellar population. A diagram of the ratio between the emission lines $[\text{OIII}]/\text{Hβ}$ versus $[3.6] - [8.0]$ colour of the SAURON Sa bulges reveals several interesting features.

The AGN we identified in Chapter 2 by having hot dusty cores ($[3.6] - [4.5] \sim 0.5$ mag) are seen offset from the other galaxies in having high log($[\text{OIII}]/\text{Hβ}) > 0.2$.
Figure 3.4: Central Spitzer [3.6]–[8.0] colour versus the SAURON gas ionization ratio [O III]/Hβ, [O III] and Hβ luminosity. Symbols denote morphological classification (Fig. 3.3). Blue circles indicate bulges that we identify by eye as having a disc-like morphology, pseudobulges (P). Red squares indicate bulges with elliptical-like morphology, classical bulges (C). In yellow we plot galaxies that we identify as AGN using the [3.6]−[4.5] colour (Chapter 2).

ratios which is unexpected for their red [3.6]−[8.0] star formation colours. For the galaxies without much star formation it is much more difficult to assess the AGN presence since stellar emission can cause similar high [O III]/Hβ ratios. The E/S0 SAURON sample has an average log([O III]/Hβ) = 0.3 ratio and in these galaxies the Hβ emission distribution shows a tight correlation with the stellar light distribution Sarzi et al. (2010). And LINER emission has values in the log([O III]/Hβ)= 0–0.5 ratio range (Ho 2008). The galaxies NGC 4383 and 5953 are similarly offset in [O III]/Hβ above what is expected for their [3.6]−[8.0] colour. NGC 4383 probably exhibits shock heating due to the biconic gas outflow associated with its starburst. Possibly NGC 5953 hosts an AGN or otherwise the galaxy shows shock heating associated with its merger. The other major merger galaxy in our sample NGC 4698
Star formation is associated with $\log([\text{O III}]/\text{H}\beta) < 0.0$ emission line ratios \cite{Falcon-Barroso+2006}. This does correlate with the Spitzer $[3.6]-[8.0]$ colour in the Sa bulges. This relation could indicate that one of the classical bulges (NGC 4596) does host some central star formation. And that some pseudobulges (NGC 3623, 5475, and 5689) are dominated by stellar emission.

Due to AGN emission and shock heating, the $[\text{O III}]/\text{H}\beta$ ratio does not appear to be a better indicator for pseudobulges than the $[3.6]-[8.0]$ colour. At best one can say that in the absence of an AGN, morphologically defined classical bulges have $\log([\text{O III}]/\text{H}\beta) > 0.2$. And the pseudobulges defined morphologically can be recognized by ratios of $\log([\text{O III}]/\text{H}\beta) < 0$. 

\cite{Falcon-Barroso+2006} also has a high $[\text{O III}]/\text{H}\beta$ ratio, higher than expected for stellar emission.
Absorption lines

Star formation is also traceable via low Mg $b$ and Fe5015 and high H$\beta$ absorption line strengths (see e.g. Allard et al. 2006). In Fig. 3.5 we see that these three indicators and the Spitzer colours show a smooth transition from old to young stellar populations, with only a few outliers.

In Mg $b$ the classical bulges we defined morphologically can be clearly spotted by having high absorption strengths ($> 4 \, \text{Å}$), and in H$\beta$ they have low absorption strengths ($< 2 \, \text{Å}$). In Fe5015 the classical bulges can not be distinguished from pseudobulges. The Mg $b$ and H$\beta$ absorption strengths thus seem to be better pseudobulge indicator than the [3.6]−[8.0] colour. The galaxies with widespread central star formation (NGC 1056, 4383, 4369, 4405 and 5953) are responsible for a kink in the diagrams, and show extra low Mg $b$ and Fe5015 and extra high H$\beta$ line strengths for the reddest [3.6]−[4.5] and [3.6]−[8.0] colours. NGC 4383 has an extremely low Fe5015 value, and an extremely red [3.6]−[4.5] colour. This can be explained being due to recent star formation.

Composite systems

These star formation diagrams reveal that three galaxies with bulges that morphologically look classical (NGC 4698, 4772 and 6501) behave quite like elliptical galaxies without any young stellar populations. The remaining classical bulge (NGC 4596) does seem to host some central star formation as seen from its low [O III]/H$\beta$ emission line ratio and can thus be understood as a composite pseudo/classical system. Also the position in the star formation diagrams of galaxy NGC 3623 with a bulge that morphologically resembles a pseudobulge argues for a composite system. The three pseudobulges without much star formation (NGC 4425, 5475 and 5689) do have younger ages as evidenced by lower Mg $b$ and higher H$\beta$ absorption line strengths than the classical bulges and are probably not composite systems.

3.3.2 Stellar kinematics

Can the presence of $\sigma$-drops, kinematically defined discs, and bars tell us more about the bulge identification? We investigate whether the structures that are found when investigating the kinematic maps in the Sa sample (Falcón-Barroso et al. 2006) agree with those found morphologically (Fig. 3.6).

Sigma-drops and kinematically defined discs

The two-dimensional stellar velocity dispersion maps reveal minima ($\sigma$-drops) caused by central discs (Bottema 1989, 1993). These $\sigma$-drops are rarely seen in ellipticals and are common in spirals (Falcón-Barroso et al. 2006). They are probably the result of recent star formation taking place in central gas discs brought in via secular evolution. In about 60 % (14/24) of the SAURON Sa’s these $\sigma$-drops are present, as measured by having ratios between the central and maximum velocity dispersion of $\sigma_{\text{cen}}/\sigma_{\text{max}} < 0.96$ (Peletier et al. 2007). These $\sigma$-drops often coincide with disc
3.3 Bulge classification versus SAURON data

Figure 3.6: Strength of the central dip in the velocity dispersion ($\frac{\sigma_{\text{cen}}}{\sigma_{\text{max}}}$), presence of a faster rotating kinematic component (kinematic disc), and the presence of kinematic signatures for a bar such as misaligned photometric and kinematic axes or boxy isophotes versus [3.6]–[8.0] bulge colour. Symbols denote morphological classification (Fig. 3.3).

structures seen in the stellar velocity maps via a sudden change in velocity close to the centre. In the following we refer to these structures as kinematically defined discs (KDs).

When we focus on bulges that we classify morphologically as classical a $\sigma$-drop is present in only one bulge: that of NGC 4596 (Fig. 3.6). This bulge also hosts a kinematic disc. This confirms the pseudo/classical composite classification inferred from the star formation diagrams. The classical bulge of NGC 4698 does host a kinematic disc, but not a $\sigma$-drop. The misalignment of this component with respect to the major axis of this galaxy argues for a major accretion event as an explanation for the KD. The absence of star formation argues against a secular evolution scenario.

Of the bulges we classify morphologically as pseudobulges 70% (13/18) have a $\sigma$-
drop and the fraction of kinematic discs is 50 %. What do these pseudobulge galaxies without a σ-drop look like? Two of the pseudobulges without a σ-drop detection show widespread star formation throughout their central region (NGC 4369 and 4383) and no central star formation concentration. The galaxies NGC 4220 and 5475 do show star formation in the Spitzer maps of their nuclei. The non-detection of σ-drops in these galaxies may be a resolution issue. This might also be true for NGC 5689. This pseudobulge galaxy has no σ-drop but does have a kinematic disc. Taking into account these limitations we can say that σ\textsubscript{cen}/σ\textsubscript{max} as traced with SAURON is a good pseudobulge indicator.

Bars

Is the presence of a σ-drop or kinematic disc linked with the presence of a bar? Misaligned photometric and kinematic axes hint at the presence of bars (Falcón-Barroso et al. 2006) in some of our galaxies (NGC 2273, 3623, 4220, 4245, 4293, 4596 and 5448). These misalignments are detected best at low galaxy inclinations. Bars in edge-on systems can be detected by means of other kinematic signatures. N-body simulations of barred galaxies suggest several bar diagnostics making use of the Gauss-Hermite series (V, σ, h\textsubscript{3}, and h\textsubscript{4}), e.g. a double-hump rotation curve, broad velocity dispersion profile with a plateau at moderate radii and a correlation between h\textsubscript{3} and V along the bar (Kuijken & Merrifield 1995; Bureau & Athanassoula 2005). In our sample five highly inclined galaxies have some of these features (NGC 3623, 4235, 4274, 5448 and 5689). Other bar diagnostics such as boxy isophotes or cylindrical rotation hint at the presence of a bar in NGC 4420 and 4425. All these diagnostics together show that about 60 % of the galaxies in our sample of Sa galaxies have a bar. This is consistent with the bar fraction of 65 % in spiral galaxies in the local universe (Sheth et al. 2008).

Of the galaxies with a classical bulge only one galaxy has a bar. The disc, seen both in the stellar velocity and stellar velocity dispersion map in the classical bulge of NGC 4596 is most likely the result of secular evolution. The galaxy displays misaligned photometric and kinematic axes which is indicative of a bar. Also some star formation appears to take place in this bulge currently. The classical bulge of NGC 7742 is surrounded by a star formation ring which is most likely brought in by an oval structure instead of by a bar. The ring could also be merger-induced (Mazzuca et al. 2006).

Of the pseudobulges that can be classified by the presence of a σ-drop 70 % (9/13) probably have a bar. Of these galaxies with a bar and a σ-drop 20 % (2/9) do not show much star formation in their bulges (NGC 3623 and 4425). The galaxies without a bar and with a σ-drop all have star formation: two are star formation ring galaxies (NGC 2844 and 5953) indicating a bar was probably present but now destroyed in these galaxies, although the SF ring in NGC 5953 is due to an interaction event, and two of the galaxies show clumpy star formation in their entire field (NGC 1056 and 4405). The bulges in these two galaxies are probably in the process of being assembled via dynamical friction.
3.4 Discussion

Relations with velocity dispersion

That the galaxies with widespread and clumpy star formation (NGC 1056, 4369, 4383 and 4405) are building their bulges via a different process becomes also evident from diagrams of stellar velocity dispersion—a proxy for stellar mass—versus [3.6]—[4.5] or [3.6]—[8.0] colour (Fig. 3.7). Together with the merger galaxy NGC 5953 they consist of low-mass galaxies (<100 km/s) with strong star formation. In the SAURON E/S0 sample one low-mass S0 galaxy (NGC 3032) has similar strong star formation. The kinematics of this galaxy argues for a merger origin (Shapiro et al. 2010). About half of the other low-mass E/S0’s also exhibit widespread star formation, but less strong and more centrally concentrated.

Other spiral galaxies bulges with low stellar velocity dispersions are offset from the [3.6]—[4.5] – σ relation seen in E/S0’s in that they have bluer colours than expected (NGC 4245, 4425 and 5475). Peletier et al. (2011) detect a similar offset in higher mass E/S0 galaxies with central discs. An intermediate-age stellar population composed of AGB stars in these discs is probably the cause of this bluening. The low-σ spiral galaxies without much star formation are thus very likely the result of the widespread and clumpy star formation that has piled up in central discs.

There are fewer spiral galaxy bulges with extreme star formation or discs of AGB stars in the intermediate mass range (σ =100 – 170 km/s). Normal secular evolution processes such as via bars or ovals that must occur in these galaxies probably result in smaller bulge built-ups than the evolution process at lower masses. In order to explain the presence of massive bulges these normal processes might occur more frequently in the lifetime of the galaxy. Shapiro et al. (2010) find that rejuvenation in fast-rotating E/S0’s takes place once every 10 Gyr. Some of these intermediate mass Sa bulges are even classified morphologically as classical bulges and might be built via dissipative collapse, minor or major mergers. This must be surely the case for the two most massive spiral galaxy bulges (NGC 6501 and 7742) with σ > 200 km/s which are comparable in mass to the bulk of the E/S0 SAURON sample.

3.4 Discussion

We have investigated five definitions for pseudobulges: 1) from the curvature, the Sérsic index, of the near-infrared radial profiles of the galaxies, 2) the mid-infrared bulge colours [3.6]—[8.0] and [8.0]—[24], 3) the bulge morphology in HST and Spitzer maps of the SAURON Sa sample, 4) using SAURON ionized gas emission and absorption line indices, and 5) using SAURON stellar kinematics.

If we use the Sérsic index n_{3.6} < 2 to define pseudobulges, we find a low pseudobulge fraction (20 %) in our sample. Many of the galaxies with n_{3.6} > 2 do show star formation in their bulges, making this definition untenable. The pseudobulge fraction increases to 50 % if we look at the mid-infrared colour definition of Fisher & Drory (2010) that pseudobulges have [3.6]—[8.0] > 1.9 mag. In Chapter 2 we have seen that our [8.0]—[24] bulge colours indicate the presence of star formation when they are larger than 2.0 mag. With this definition [8.0]—[24] > 2.0 mag, which corresponds with [3.6]—[8.0] > 1.0 mag, the pseudobulge fraction increases to 70 %.
Figure 3.7: Central stellar velocity dispersion versus [3.6]–[4.5] and [3.6]–[8.0] Spitzer colour. Symbols denote morphological classification (Fig. 3.3). The lines indicate the relations for the SAURON ellipticals and lenticulars from Peletier et al. (2011), for one (striped line) and one-eighth of an effective radius (solid line). In grey elliptical and lenticular galaxy gradients going from one-eighth of an effective radius $R_e/8$ to one effective radius $R_e$ (Kuntschner et al. 2010; Peletier et al. 2011) or $R_e$ data (Shapiro et al. 2010).
Using the morphological classification that pseudobulges have similar flattening
to that of that of the outer disc and/or having irregular or bar-like isophotes in HST
and 3.6 µm images and that classical bulges have smooth elliptical-like isophotes,
we find a pseudobulge fraction of 80%. With this definition a galaxy is classified
as a pseudobulge if it contains a central disc. This disc does not have to dominate
the bulge, although it might. According to this definition a galaxy can have both
a classical and a pseudobulge. All the classical bulges defined morphologically have
colours [3.6]−[8.0] < 1.0 mag and $n_{3.6} > 3$, although NGC 7742 might be an exception
being morphologically a classical bulge and which is surrounded with a star formation
ring: its bulge colour is [3.6]−[8.0] < 1.9 mag and its Sérsic index $n_{3.6} \sim 2$.

We compared this new morphological definition for recognizing pseudobulges and
classical bulges with the SAURON diagnostics of star formation and stellar disc-like
kinematics and find intriguing results about the assembly of the SAURON Sa galaxies.

Even though using our morphological classification most galaxies are classified as
having a pseudobulge, a comparison with kinematics maps shows that bulges that
morphologically have been classified as being classical can still contain discs. This is
the case for NGC 4596, which contains a σ-drop as measured by if $\sigma_{\text{cen}}/\sigma_{\text{max}} < 0.96$. This could indicate that a secular evolution process has taken place in this bulge.
That σ-drops are not present in the classical bulges of NGC 4698, 4772, and 6501,
could indicate that these bulges are the result of a major merger, a series of minor
mergers and/or early dissipative collapse. The central regions of NGC 4772 show gas
that counter-rotates with respect to the stars, which could indicate a recent minor
merger. The central stellar region of NGC 6501 is old [Peletier et al. 2007] and
massive ($\sigma \sim 230$ km/s) and this hints at a scenario of early dissipative collapse.

As far as pseudobulges are concerned: 70% of them show a σ-drop. It could be
that in the remaining 30% σ-drops are missed due to low resolution of SAURON.
However, we also notice that two pseudobulges without a σ-drop host extreme star
formation in their central regions (NGC 4369 and 4383), but lack a central star
formation concentration. The presence of a σ-drop in the two other galaxies with
widespread star formation (NGC 1056 and 4405) suggests that in these 4 galaxies
the pseudobulges are formed rapidly through a process of dynamical friction. We
investigated the relation between bars and σ-drops: of the pseudobulges with a σ-
drop 70% have a bar. Given that a spiral galaxy probably undergoes 3 to 4 bar
production and destruction cycles per lifetime it is difficult to tell if these σ-drops
are the result of secular evolution. If so, the majority of pseudobulges have probably
been formed via the secular evolution processes related to bars or ovals (14/19) in
galaxies of intermediate mass ($\sigma \sim 110$ km/s).

3.5 Summary and conclusions

For understanding the nature and formation of bulges it is important to understand
their properties. If there are two kinds of bulges, named pseudobulges and classical
bulges, there should be an easy and straightforward way to classify them. We have
studied Spitzer colours, Sérsic indices, SAURON stellar kinematics, ionized gas emis-
sion and absorption line indices to define a classification method that can classify pseudobulges in the SAURON Sa sample on a physical basis.

Following these criteria, our best method is a morphological classification where central components that have a similar flattening to that of the outer disc and/or irregular or bar-like isophotes in *HST* and 3.6 μm images are called pseudobulges, and objects with smooth, elliptical-like isophotes are classified as hosting classical bulges. Using this definition 5/24 galaxies have a classical bulge, while 19/24 show a pseudobulge.

If the Sérsic index, a measure of the radial curvature of the surface brightness profile, is used to classify bulges, fewer pseudobulges are found. In this way, a class of galaxies with red [3.6]-[8.0] colours and star formation in their central regions is classified as classical bulges. This class has not been noted in Fisher & Drory (2010), since it is under-represented in that paper.

All the classical bulges defined morphologically have colours [3.6]−[8.0] < 1.0 mag and \( n_{3.6} > 3 \), suggesting these limits can be used to recognize pseudo- and classical bulges. A comparison with the sample of 146 RC3 disc galaxies of Fisher & Drory (2010) suggests that the fraction of classical bulges is about 20 % in Sa galaxies, 10 % in Sb galaxies and none in later type galaxies.

Pseudobulges defined using our morphological classification not necessarily coincide with the bulge that is obtained using photometric decomposition of a spiral into an exponential disc and a spherical bulge. The pseudobulge here is a central disc component with dust, gas and often central star formation. And the discs often coincide with central velocity dispersion dips. Of the bulges we classify morphologically as pseudobulges 70 % have a \( \sigma \)-drop, indicating that \( \sigma \)-drops are a good tool to find pseudobulges. The stellar kinematics indicate that these bulges are assembled in a secular evolution process via bars, ovals or dynamical friction. The classical bulges are more likely the result of a major merger, a series of minor mergers and/or early dissipative collapse.