CENTRAL STAR FORMATION AND PAH PROFILES IN PSEUDOBULGES AND CLASSICAL BULGES

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ABSTRACT

I use Spitzer 3.6–8.0 μm color profiles and surface brightness profiles of polycyclic aromatic hydrocarbons (PAHs) to compare the radial structure of star formation in pseudobulges and classical bulges. Pseudobulges are “bulges” that form through secular evolution, rather than mergers. In this study, pseudobulges are identified using the presence of disklike structure in the center of the galaxy (nuclear spirals, nuclear bars, and high ellipticity in bulge); classical bulges are those galaxy bulges with smooth isophotes that are round compared to the outer disk and show no disk structure in their bulge. I show that galaxies structurally identified as having pseudobulges have higher central star formation rates than those of classical bulges. Furthermore, I also show that galaxies identified as having classical bulges have remarkably regular star formation profiles. The color profiles of galaxies with classical bulges show a star-forming outer disk with a sharp change, consistent with a decline in star formation rates, toward the center of the galaxy. Classical bulges have a nearly constant inner profile (r ≤ 1.5 kpc) that is similar to elliptical galaxies. Pseudobulges in general show no such transition in star formation properties from the outer disk to the central pseudobulge. Thus, I conclude that pseudobulges and classical bulges do in fact form their stars via different mechanisms. Furthermore, this adds to the evidence that classical bulges form most of their stars in fast episodic bursts, in a similar fashion to elliptical galaxies, whereas pseudobulges form stars from longer lasting secular processes.

Subject headings: galaxies: bulges — galaxies: formation — galaxies: spiral — galaxies: starburst

1. INTRODUCTION

Fundamental to understanding the formation of galaxies is understanding the mechanisms responsible for forming the stars in these galaxies. Bulges are thought to have formed their stars in and shortly after the fast, violent process of merging stellar systems (Schweizer 2005). However, secular evolution can make bulges as well. Secular evolution is the slow rearrangement of material within a galaxy. Kormendy & Kennicutt (2004, hereafter KK04) give a thorough review of the properties of bulges thought to be built by secular evolution and show many examples of pseudobulges that could not have been made by mergers. Secular drivers often work by causing gas to lose angular momentum and fall to the center of the galaxy. This effect is quite pronounced in galaxies with bars. Hydrodynamical simulations of gas in barred potentials by Athanassoula (1992) show that shocks on the leading edge of bars cause this angular momentum loss. Observations of velocity contours crowding on the leading edges of bars support this theory (Downes et al. 1996; Regan et al. 1999). It is also well known that the surface density of star formation scales as a power law with the surface density of gas $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5}$ (Kennicutt 1998). Therefore, if enough gas is driven to the center of a disk galaxy, star formation will convert the gas into a pseudobulge. KK04 give a connection between interstellar medium and star formation properties to a specific kind of pseudobulge (those that have star-forming nuclear rings). They show that star formation rate (SFR) densities for circumnuclear rings are higher than their associated outer disks. Furthermore, KK04 estimate the timescale on which circumnuclear disks are converted into stellar disks, giving an estimate ~0.2–2 Gyr for pseudobulge formation. Therefore, active star formation should be present in many present-day pseudobulges.

Recent work on star formation in the central kiloparsec of galaxies has shown that many bulges are forming stars and that secular evolution may be responsible. Regan et al. (2001) compare the radial distribution of CO to the stellar light profiles in 15 spiral galaxies. They find that eight of the 15 galaxies show an excess of CO emission in the “bulge” region of the galaxy and, furthermore, that the central CO radial distribution is similar to that of the stellar light. Heffler et al. (2003) find that 45% of the galaxies in the BIMA Survey of Nearby Galaxies have a peak CO emission within the central 6", while many galaxies have a central hole in the CO map. This suggests that there may be multiple types of molecular gas distributions in galaxies. Regan et al. (2001) note that this could be the consequence of a bulge being formed via secular evolution. Stellar age gradients in bulges of disk galaxies suggest multiple formation mechanisms as well. Moorby & Holtzman (2005) find that many bulges follow correlations with ellipticals. However, many bulges have younger stellar populations in the center of the bulge, suggesting an outside-in formation.

Sakamoto et al. (1999) compare the concentration of molecular gas in the center of galaxies to the frequency of drivers for secular evolution (i.e., bars). They find, with a sample of 20 galaxies, that molecular gas is more centrally concentrated in galaxies with bars. Recently, Sheth et al. (2005) showed that barred galaxies have more centrally concentrated gas than galaxies without bars. However, they do find a few barred galaxies that do not show a large presence of molecular gas.

In this Letter, I tie together indicators of SFRs with other measures of secular evolution. I show that galaxies with any central structure indicative of pseudobulges exhibit an enhanced amount of star formation (as indicated by the 3.6–8.0 μm color profile and PAH emission). I also show that timescales are plausible to assume that these pseudobulges are being built by mostly star formation.

2. PSEUDOBULGE IDENTIFICATION

Results from Hubble Space Telescope (HST) surveys of centers of late-type galaxies (Carollo et al. 2001) have shown that many galaxies harbor nuclear spirals, bars, and rings; these are disk phenomena and are not possible in a hot stellar system.
stars at the rate of \( \frac{1}{2005} \) find that the central 500 pc of this galaxy is forming entire pseudobulge appears to exhibit spiral structure. Koda et al. (2005) find no molecular gas in the center. This classical bulge is not actively forming stars. It is worth noting that the presence of a little dust in the center of a galaxy does not necessarily mean that the bulge is a pseudobulge. Conversely, if the bulge is featureless and more round than the outer disk, the bulge is actually a pseudobulge. This galaxy has little to no dust emission in the bulge. Helfer et al. (2003) find no molecular gas in the center. This classical bulge is not actively forming stars. It is worth noting that the presence of a little dust in the center of a galaxy does not necessarily mean that the bulge is a pseudobulge.

KK04 tie all of this together into a single picture, suggesting that bulges exhibiting these properties are formed through secular evolution. In this study, I classify galaxies as having a pseudobulge using bulge morphology; thus, if the bulge is or contains a nuclear bar, nuclear spiral, nuclear ring, and/or the flattening in the central region is similar to the flattening in the outer disk, the bulge is actually a pseudobulge. Conversely, if the bulge is featureless and more round than the outer disk, the bulge is called a classical bulge.

Figure 1 illustrates a typical example of what I identify as a pseudobulge (left) and a classical bulge (right). Notice first that the classical bulge (NGC 2841) has a smooth stellar light profile. There is no reason evident in the image to think that this galaxy harbors a pseudobulge. This galaxy has little to no dust emission in the bulge. Helfer et al. (2003) find no molecular gas in the center. This classical bulge is not actively forming stars. It is worth noting that the presence of a little dust in the center of a galaxy does not necessarily mean that the bulge is a pseudobulge.

Lauer et al. (2005) provide many examples of nuclear dust in elliptical galaxies, which certainly did not form through secular evolution. Thus, merely relying on visual identification of dust in bulges for pseudobulge identification should be done with care.

NGC 4536 is an example of a galaxy with nuclear spiral structure and patchiness (i.e., a pseudobulge). A decomposition of the stellar surface brightness profile shows that the pseudobulge dominates the light profile out 8.5. This implies that the entire pseudobulge appears to exhibit spiral structure. Koda et al. (2005) find that the central 500 pc of this galaxy is forming stars at the rate of \( \sim 9 \, M_\odot \, yr^{-1} \, kpc^{-2} \).

I carry out this classification process on disk galaxies in the Spitzer archive data, spanning the Hubble types S0 to Sc. I select from that only galaxies that also have available visible band images in the HST archive, for pseudobulge identification. Three elliptical galaxies are added for comparison. Galaxies in which bulge classification is uncertain, or those with bright active galactic nuclei, are not included. The total sample is 50 galaxies.

### 3. PAH EMISSION AND COLOR PROFILES

I use the Spitzer Infrared Array Camera 8 \( \mu \)m channel as an indicator of SFRs. The usefulness of IR flux as an SFR indicator has been proven by Wu et al. (2005). They show that luminosities a stellar light–adjusted 8 \( \mu \)m channel, \( L(\text{PAH}) = L(8 \, \mu \text{m}) - 0.26L(3.6 \, \mu \text{m}) \), correlate well for giant galaxies with other star formation indicators, namely, radio luminosity and H\( \alpha \) flux.

The aim of this Letter is to determine if bulges that are believed to have formed via secular evolution are more likely to be forming stars actively than bulges believed to have formed in mergers. I expect to find that galaxies that are found to harbor pseudobulges should have a more centrally concentrated distribution of PAH emission than galaxies found to have classical bulges. To test this claim, I calculate surface brightness profiles of Spitzer fluxes in 3.6 and 8 \( \mu \)m. This allows me to compare the distribution of stars to that of PAH emission in each galaxy.

The disparity in star formation properties between pseudobulges and classical bulges is evident in the 3.6–8 \( \mu \)m color profiles, shown in Figure 2 (left panel). Note that the 8 \( \mu \)m data in the color profile is not corrected for stellar light. In these color profiles, regions with redder colors are more actively forming stars (higher PAH emission per stellar luminosity). Figure 2 shows that those galaxies identified as having a pseudobulge do not have markedly different color profiles in their bulges as compared to their associated outer disks. Perhaps more compelling is the regular behavior of the classical bulge profiles. In general, classical bulges show a marked change in color profile, getting bluer, indicating a change toward smaller SFRs. The 3.6–8 \( \mu \)m colors of classical bulges agree quite well.
Fig. 2.—Profiles of all 50 galaxies considered in the sample. The left panel shows color profiles of all galaxies, the middle panel compares the averages of pseudobulges and classical bulges, and the right panel shows the average profiles of each Hubble type.

Fig. 3.—Both panels show the specific SFR of the central 1500 pc (star formation normalized by the stellar mass). The left panel shows the dependence of the specific SFR of bulges and pseudobulges on Hubble type. The right panel shows the specific star formation of the central 1500 pc plotted against secular driving mechanism (B = bar, O = oval, and N = neither bar nor oval).

with those of elliptical galaxies (black lines). Also shown (middle panel) is the averaged profile of the pseudobulges (red line) and classical bulges (blue line). The average profile of the pseudobulges shows a modest decline but is roughly constant across the entire profile, especially compared to the average profile of the classical bulges, which shows the decrease in SFRs in the centers. Similar research has been reported claiming a connection between optical light profiles and central PAH emission (Regan et al. 2005).

Pieces of the puzzle of bulge formation are fitting together. Those galaxies identified as pseudobulges are forming their stars at similar rates to outer disks. KK04 state that pseudobulge recognition is possible because pseudobulges have a memory of their disky past. This is generally referring to pseudobulges having cold stellar dynamics, like disks. It appears that this statement applies to star formation as well; the processes that make pseudobulges are believed to be disk processes. Wyse et al. (1997) remark that “bulges are more like their disk than they are like each other.” Comments like this reflect a history in which all bulgelike structures were thought to have come from similar formation events. However, one sees clearly that separating out pseudobulges from (merger built) classical bulges results in quite regular star formation properties in classical bulges.

4. VARIATION WITH MORPHOLOGY

The idea that secular evolution becomes more important at later Hubble types is well accepted (KK04 and references therein). If pseudobulges build their mass slowly, then it should be less likely to find a large pseudobulge because it would take longer to form. Previous studies have found that earlier type spirals that show molecular gas emission are emitting at higher luminosities than later types (Sheth et al. 2005). This is actually not surprising. Sa and S0 pseudobulges do exist (KK04). Also, the Hubble sequence is one of decreasing bulge-to-disk ratio; thus, secular evolution may be either more pronounced or longer lived in galaxies that are to become Sa galaxies. To account for variation in bulge mass, I calculate specific SFRs (SFR normalized by the total stellar mass of the same region). Stellar bulge masses are calculated by integrating the 3.6 μm emission within 1.5 kpc and assuming $M/L_{3.6} = 1$. Figure 3 shows the specific SFRs for the central 1.5 kpc of each disk galaxy in my sample. In this sample, pseudobulges in Sa galaxies have roughly the same or lower amounts of central star formation per unit mass than later types. Although, it is worth noting that any study of Hubble types with a sample size of 20–50 galaxies will inevitably involve small number statistics.

The rightmost panel of Figure 2 shows that star formation dominates the inner kiloparsec of late-type galaxies (Sbc and Sc) and has moderate effects on intermediate types (Sa and Sb) but there is little to no central star formation in early types (E and S0). The right panel of Figure 3 shows the dependence of specific SFRs on secular driving mechanism. It also illustrates the frequency of pseudobulges and bulges in galaxies with ovals (O), bars (B), and neither (N). The result is that the average amount of central SFRs for galaxies with ovals and bars is about the same. Galaxies with a regular spiral pattern (neither bar nor oval) show on average lower SFRs. This is in agreement with the findings of Sakamoto et al. (1999) and Sheth et al. (2005). I find, as Sheth et al. do, that some barred galaxies exist that are not on the high end of SFRs. I also find that these galaxies are not pseudobulges, possibly implying that secular evolution in galaxies with a preexisting classical bulge is limited or more difficult. Another possibility is the proposal of Jogee et al. (2005) that there are multiple stages of secular evolution. In this case, early stages are not actively forming stars. These barred non–star-forming bulges could be in the earlier (prestarburst) stages of evolution.
5. CONCLUSIONS

In this Letter, I have calculated the PAH profiles and color profiles for 50 galaxies spanning the Hubble types E to Sc. I use HST images to identify pseudobulges (bulges made through secular evolution) and classical bulges (bulges made through hierarchical mergers). I interpret the PAH emission as being directly proportional to the SFR, as shown by Wu et al. (2005). And thus I compare the incidence of active central star formation to the presence of pseudobulge or classical bulge structures.

Pseudobulges are shown to have higher specific SFRs than classical bulges. As well, the PAH emission profiles of pseudobulges are brighter and more centrally concentrated. I also show that galaxies with bars or ovals on average have brighter central PAH emission than galaxies without strong drivers of secular evolution, which is in agreement with previous findings.

As a sanity check, I can calculate the time it would take the pseudobulges in my sample to form their associated stellar masses. This is done by simply inverting the specific SFRs in Figure 3. I calculate growth times typically 0.1–5.0 Gyr, with a median of 0.6 Gyr. Thus, assuming that the star formation is a prolonged event, it is plausible that these galaxies have had sufficient time to form a bulge with this amount of star formation. And it is worth noting the similarity to the gas consumption timescales calculated in KK04, implying that secularly driven star formation plays a strong role in forming pseudobulges, as well as the agreement with the stellar populations work of Thomas & Davies (2006), who show that many bulges “must have experienced star formation events involving 10%–20% of their mass in the past 1–2 Gyr.”

The behavior of SFRs in mergers is well studied (see Schweizer 2005 for review); the expectation is that shocks will induce massive starburst and exhaust available fuel relatively quickly. Thus, we do not expect to find merger-built bulges (or elliptical galaxies) that are actively forming stars. The response of gas to form stars due to secular evolution is less well understood, theoretically. Secular evolution will funnel gas inward (see KK04 for a review). Therefore, our finding that galaxies with pseudobulges are much more likely to be actively forming stars is consistent with the formation of a pseudobulge via secular evolution.

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