The Coexistence of Classical Bulges, Pseudobulges, and Supermassive Black Holes

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Abstract. Some S0 and early-type spiral galaxies possess “composite bulges”; in these galaxies, the photometric bulge – the central stellar light in excess of the disk light – is composed of both a “(disky) pseudobulge”, with a flattened, disklike morphology and relatively cool stellar kinematics, and a rounder, kinematically hot “classical bulge” embedded within. I speculate that supermassive black holes in such galaxies may correlate with the classical-bulge component only, and not with the pseudobulge component; preliminary comparisons with SMBH masses appear to support this hypothesis.

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INTRODUCTION

There are now several well-established correlations between central supermassive black holes (SMBHs) and their host galaxies. These take the form of correlations between the SMBH mass and properties of the bulge, such as its central stellar velocity dispersion, luminosity, or total mass, and are thought to reflect strong ties – perhaps even identities – between the mechanisms that fuel SMBH growth (and accompanying nuclear activity) and the buildup of bulges. The term “bulge” is usually taken to mean a kinematically hot stellar spheroid. In the case of elliptical galaxies, this is the galaxy itself; in the case of disk galaxies (S0 and spirals), this is assumed to be the central “photometric excess” – the excess stellar population above that of the galaxy disk.

If all disk-galaxy bulges were the same kind of structure as elliptical galaxies – which is in fact the traditional view of bulges – then things would be relatively simple: theorists could argue for mechanisms which fuel SMBHs and grow bulges (e.g., via rapid, violent mergers and accompanying starbursts) across the Hubble sequence. But recent observations and arguments suggest that the “bulges” in many disk galaxies may be a different kind of beast: a disklike structure which has developed slowly (“secularly”) out of the disk and retains many disk properties [see the review by 8]. If SMBHs correlate with such “pseudobulges” to the same degree as they do with classical bulges and ellipticals, then explaining these correlations becomes much harder, because the respective formation mechanisms may be very different.

Here, I discuss the idea that some galaxies may have “composite bulges,” with both classical bulges and pseudobulges [see also 5, 1]. I conjecture that SMBHs in such galaxies may correlate with the classical bulge component alone, rather than with the
pseudobulge, thus preserving the SMBH-bulge correlations as correlations between SMBHs and kinematically hot spheroids. Observations are currently in progress to test this hypothesis.

**DEFINITIONS AND AN EXAMPLE**

The term **photometric bulge** means the central excess stellar light of the galaxy, above that of the (extrapolated) exponential disk, regardless of morphology or kinematics. The photometric bulge can be identified by standard bulge-disk decompositions, and is in fact what most people doing bulge-disk decompositions mean by “bulge.” If some or all of the photometric bulge turns out to be morphologically disklike – flattening similar to that of the outer disk, possibly containing disk features such as nuclear bars and rings – and kinematically cool (e.g., local stellar $V/\sigma > 1$), then this a (**disky**) **pseudobulge**. (“ Disky” is used to avoid confusion with other structures which have been called pseudobulges, such as the vertically thickened “boxy/peanut-shaped bulges” produced by bars.) Finally, a central component which is clearly rounder than the outer disk and which is kinematically hot is a **classical bulge**, under the hypothesis that this is closer to what has been traditionally meant by the term “bulge.”

NGC 4371 is a barred S0 in the Virgo Cluster. The left-hand panels of Fig. 1 show the major-axis surface-brightness profile (based on ground-based and HST optical images). Superimposed is a “naive” bulge/disk decomposition, where I assume that the light is the sum of an outer exponential and an inner Sérsic component. The photometric bulge is then identified as the region where the Sérsic component dominates ($r < 30''$).

Closer examination shows that part of the photometric bulge region is quite elliptical, and harbors a bright nuclear ring with radius $\sim 10''$ [3]. Kormendy [7] used the ratio of the peak stellar velocity in this region to the central velocity dispersion ($V_{\text{max}}/\sigma_0$) to argue that the photometric bulge was rotating faster than an isotropic oblate rotator (a simple model for classical bulges) would. The lower-right panel of Fig. 1 shows $V_{\text{dp}}/\sigma$ as a function of radius, where $V_{\text{dp}}$ is the stellar velocity deprojected to its in-plane value and $\sigma$ is the stellar velocity dispersion. This ratio rises to $\sim 1.5$ in the vicinity of the nuclear ring, indicating that the stellar kinematics are (relatively) cool and disklike.

As the residuals in the lower-left panel of Fig. 1 indicate, the surface-brightness profile in the photometric bulge region is not actually a simple Sérsic profile. We can model the inner $\sim 30''$ as the sum of an exponential and a separate, inner Sérsic component (along with a small contribution from the nuclear ring; lower middle panel of Fig. 1). When we do this, we see that this inner Sérsic component matches quite well with a region of rounder isophotes, at $r < 5''$. Moreover, $V_{\text{dp}}/\sigma$ has a plateau of $\sim 0.7$ in this region, suggesting that we are seeing a separate, kinematically hotter component. This, then, is evidence for a classical bulge embedded within the disky pseudobulge.

**RESULTS AND DISCUSSION**

A total of ten composite-bulge systems have been identified and analyzed in at least preliminary fashion; all but two of these are S0 galaxies (the others are early-type...
FIGURE 1. The composite bulge of NGC 4371. Upper left: \(R\)-band isophotes, showing the outer disk, the bar, and photometric bulge; red line indicates major axis. Lower left: major-axis surface brightness profile with bulge-disk decomposition; vertical dashed green line indicates boundary of photometric bulge. Upper middle: inner isophotes, showing disky pseudobulge region. Lower middle: surface brightness profile with bulge/disk/nuclear-ring decomposition (not the same as the first decomposition); gray zone indicates the classical bulge region. Upper right: ellipse fits to isophotes. Lower right: \(V_{dp}/\sigma\) as a function of radius (see text), based on folded major-axis long-slit spectra.

spirals). Although the collection assembled so far is not based on any rigorous, unbiased sample, comparison with a partially complete survey of local S0 galaxies suggests that at least \(\sim 20\%\) of S0 galaxies may have composite bulges.

In these systems, the majority of the stellar light making up the photometric bulge is in the disky pseudobulge; the classical bulge is typically only \(\sim 25\%\) as bright as the pseudobulge component. Compared to the whole galaxy, the classical bulges have a median B/T of only 0.1, with a range of 0.02–0.22. They have Sérsic indices ranging from 1.3 to 3.4, with a median value of 2.0, and are quite compact: half-light radii range from 70 pc to 1000 pc (median = 160 pc). Note that even the smallest of these classical bulges is more than an order of magnitude larger than a typical nuclear star cluster \([R_e = 2–5 \text{ pc}; 2]\), and there is at least one clear case of a nuclear star cluster existing as a distinct component inside the classical bulge.

The coexistence of classical bulges and pseudobulges suggests a potentially interesting hypothesis concerning the relationship between central supermassive black holes and their parent galaxies. If SMBHs correlate (and are formed in concert with) photometric bulges, then they should correlate with pseudobulges in pseudobulge-dominated cases. (Which in turn implies that pseudobulge and SMBH growth must be linked in a fashion not too dissimilar from that linking SMBH mass and elliptical galaxies, despite the radically different scenarios for pseudobulge and elliptical galaxy growth.) On the other hand, if the true correlation is between SMBHs and kinematically hot spheroids, then we should expect the strongest correlation to be with the embedded classical bulge rather than with the photometric bulge. It is unclear how one would separate out classical and pseudobulge contributions to the central velocity dispersion; but separating out
FIGURE 2. The black hole–bulge relation (SMBH mass versus $K$-band luminosity of the photometric bulge), based on Erwin & Gadotti [4], with additional data from Nowak et al. [9]. The five circled points are composite-bulge galaxies; the horizontal black arrows link the luminosity of the entire photometric bulge (right) to the luminosity of the embedded classical-bulge component only (left). Note that the latter are a better match to the overall correlation (diagonal red line). Blue downward arrows indicate upper limit on SMBH mass for NGC 3945 from Gültekin [6].

their respective contributions to bulge luminosity (or stellar mass) is relatively simple. Fig. 2 is a preliminary exploration of this question: do SMBH masses correlate with total photometric bulge luminosities, or only with the classical bulge components? The figure includes recent SMBH measurements with VLT-SINFONI for two of the composite-bulge systems [9]; further observations of other candidates are being analyzed.

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