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A connection between bulge properties and the bimodality of galaxies

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Abstract. The global colors and structure of galaxies have recently been shown to follow bimodal distributions. Galaxies separate into a "red sequence", populated prototypically by early-type galaxies, and a "blue cloud", whose typical objects are late-type disk galaxies. Intermediate-type (Sa-Sbc) galaxies populate both regions. It has been suggested that this bimodality reflects the two-component nature of disk-bulge galaxies. However, it has now been established that there are two types of bulges: "classical bulges" that are dynamically hot systems resembling (little) ellipticals, and "pseudobulges", dynamically cold, flattened, disk-like structures that could not have formed via violent relaxation. Alas, given the different formation mechanisms of these bulges, the question is whether at types Sa-Sbc, where both bulge types are found, the red-blue dichotomy separates galaxies at some value of disk-to-bulge ratio, B/T, or, whether it separates galaxies of different bulge type, irrespective of their B/T. In this paper, we identify classical bulges and pseudobulges morphologically with HST images in a sample of nearby galaxies. Detailed surface photometry reveals that: (1) The red – blue dichotomy is a function of bulge type: at the same B/T, pseudobulges are in globally blue galaxies and classical bulges are in globally red galaxies. (2) Bulge type also predicts where the galaxy lies in other (bimodal) global structural parameters: global Sérsic index and central surface brightness. Hence, the red – blue dichotomy is not due to decreasing bulge prominence alone, and the bulge type of a galaxy carries significance for the galaxy's evolutionary history.

1. Introduction

Recent large surveys led to the realization that galaxies are bimodally distributed in the color–magnitude plane, separating into a red sequence and a blue cloud (Strateva *et al.* 2001; Balogh *et al.* 2004; Baldry *et al.* 2004; Liske *et al.* 2003; Driver *et al.* 2006). Other parameters, such as luminosity, surface density, concentration, and stellar populations follow this bimodality.

How does this relate to the Hubble sequence? Elliptical (E) galaxies, which are the prototypical red-sequence objects, occupy one end of the Hubble sequence. On the other extreme we find pure disk galaxies (Sd-Sm), which populate the blue cloud. Intermediate-type (Sa-Sbc) galaxies form a sequence in bulge-to-total ratio, B/T, and bridge the red and blue loci in the color–magnitude plane. It is therefore reasonable to attribute the bimodality seen in colors of galaxies to this bulge-disk two-component nature of galaxies, a point recently affirmed by Driver *et al.* (2006). However, colors of disks and their associated bulges are correlated (Peletier & Balcells 1996; de Jong 1996; MacArthur *et al.* 2004). Additionally, there are at least two distinct types of bulges, where "bulge" is defined as the excess light over the inward extrapolation of the surface brightness profile of the outer disk.

Many bulges are dynamically hot systems resembling elliptical galaxies ("classical bulges"). They are assumed to form in major mergers. These bulges are called. Other

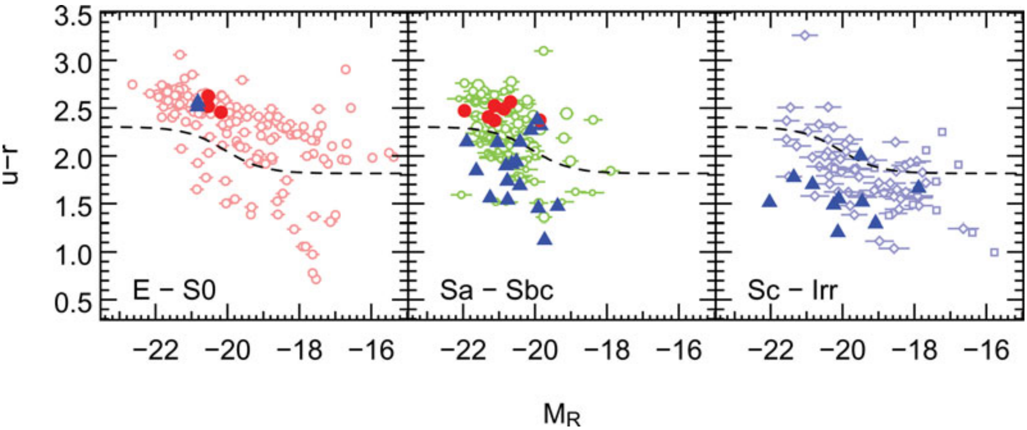

Figure 1. The location of three different galaxy populations is shown in global color vs. total magnitude space, from left to right: early-type (E-S0), intermediate-type (Sa-Sbc), and late-type (Sc-Irr). Galaxies identified as having pseudobulges are represented by filled triangles, galaxies with classical bulges are shown as filled circles. Galaxies without bulge identification are shown as open symbols for comparison. The dashed line separates the red sequence from the blue cloud following Baldry *et al.* (2004).

bulges have structure and kinematics resembling that of disks ("pseudobulges"). These are dynamically cold (Kormendy 1993). They have flattening similar to that of the outer disk (Kent 1985; Kormendy 1993; Fathi & Peletier 2003; Kormendy & Fisher 2005; Kormendy *et al.* 2006). Also, they may have embedded secondary bars, rings, and/or spiral structure (Carollo *et al.* 1997). They are thought to form through slow rearrangement of disk material. Kormendy & Kennicutt (2004) give a comprehensive review of the field. See also Kormendy, in this volume.

This dichotomy among bulges imposes us to ask two questions. Do galaxies with pseudobulges behave like (bulgeless) pure disk galaxies? Secondly, is the location of a galaxy with respect to the (color) bimodality determined by the relative prominence of its bulge and disk components alone or does the type of the bulge play a role? The question becomes whether at intermediate Hubble types of Sa-Sbc, where both bulge types are found, the color bimodality separates galaxies at some bulge-to-total ratio, or, whether it separates galaxies of different bulge type, irrespective of bulge-to-total ratio (or neither).

In Drory & Fisher (2007), we define a sample of 39 galaxies spanning Hubble types S0 to Sc by cross referencing the Third Reference Catalog of Bright Galaxies (RC3; de Vaucouleurs *et al.* 1991), the Sloan Digital Sky Survey Data Release Four (SDSS - DR4) database (Adelman-McCarthy *et al.* 2006), and the Hubble Space Telescope (HST) archive. We require that the galaxies have inclination $i \leqslant 60°$ to reduce the effect of dust. We will use the RC3 Hubble classification, colors and total magnitudes from SDSS images, and surface brightness profile fits to combined HST and SDSS surface photometry. We identify pseudobulges and classical bulges using the high-resolution HST images. We maintain a roughly even sampling of Hubble types from S0 to Sc.

In this study, we classify galaxies as having a pseudobulge using bulge morphology; if the "bulge" is or contains a nuclear bar, nuclear spiral, and/or nuclear ring 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. Kormendy & Kennicutt (2004) explain and justify these criteria and show examples. See also Drory & Fisher (2007) for a discussion of the sample and the classification.

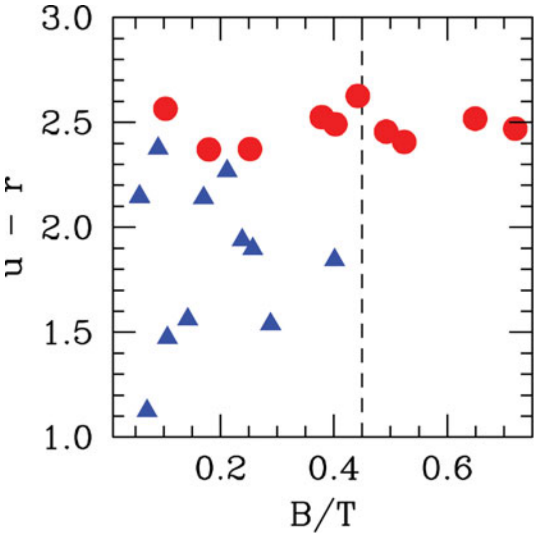

Figure 2. The distribution of bulge-to-total ratios, B/T, of intermediate type (Sa-Sbc) galaxies with pseudobulges (filled triangles) and classical bulges (filled circles) with respect to their global $u-r$ color. The dashed line marks $B/T = 0.45$.

Fig. 1 shows the location of galaxies with classical bulges (round symbols) and galaxies with pseudobulges in our sample in the $u-r$ vs. M_r plane. Note that we plot the total galaxy color and total magnitude, not the bulge color and magnitude. We merely label the galaxies by their bulge type. As a reference sample, we also plot 542 galaxies selected from the intersection of the SDSS-DR4 spectroscopic catalog and the RC3.

Late types (Right panel in Fig. 1). Late type galaxies (type Sc and later) are almost entirely on the blue sequence (e.g. Strateva *et al.* 2001). The reddest galaxies in this bin are most likely affected by dust extinction. We emphasize that the panel with Sc-Irr galaxies does not contain a single classical bulge. As the Hubble sequence progresses toward later types, galaxies tend to have small bulges or no bulge at all. This is indicative of a less violent past, as it is very likely that these galaxies have not experienced a merger event that would have formed a (classical) bulge since the time of formation of their disks. The fact that these galaxies seem to contain pseudobulges if they have a bulge at all, provides a strong reinforcement of this statement.

Intermediate types (Middle panel in Fig. 1). Nearly all Sa-Sbc galaxies with pseudobulges are bluer than the red–blue divide, while all the galaxies with classical bulges are redder than the divide. This is not simply the consequence of the pseudobulge galaxies having lower bulge-to-total ratios than the classical bulge galaxies. In fact, in the range of B/T values spanned by galaxies with pseudobulges we find plenty of classical bulge galaxies as well. This is illustrated in Fig. 2, where we plot global $u-r$ against B/T.

In our sample, galaxies on the red sequence with classical bulges have B/T ratios as low as 10%. Galaxies with pseudobulges have B/T ratios as high as 40%. The majority of galaxies with classical bulges in our (small) sample have B/T values in the same range as the galaxies with pseudobulges. Even at the lowest $B/T \sim 0.1$ values in our intermediate type Sa-Sbc galaxies, the assignment of a galaxy to the red sequence or the blue cloud is predicted by its bulge type. Classical bulge galaxies extend to greater B/T values than do pseudobulge galaxies. Pseudobulges form secularly by rearranging disk material. Therefore it seems unlikely that a disk would be able to make a pseudobulge equal in size to itself ($B/T \simeq 0.5$) through secular evolution.

Early types (Left panel in Fig. 1). The early-type bin (E - S0) is almost entirely populated by red sequence galaxies. There are three galaxies that we identify as harboring pseudobulges in this panel. All three pseudobulges are in S0 galaxies and these are on the red sequence. The processes that are thought to make S0 galaxies (e.g. gas stripping by ram pressure, harassment; Moore *et al.* 1996) operate independently of the processes that make bulges. It is reasonable to believe that the evolution which makes a galaxy an S0 happens independently of the secular evolution that makes a pseudobulge (see the discussion in Kormendy & Kennicutt 2004). Therefore the position of S0 galaxies in color–magnitude space may be due to separate phenomena, rather than posing a counter example to our hypothesis.

Concluding this discussion, we find that the red–blue bimodality cannot be a function of decreasing bulge prominence alone. Our results show that it is a function of bulge type. Pseudobulges are in blue galaxies and classical bulges are in red galaxies. Furthermore, galaxies with pseudobulges behave just like pure disk galaxies if we compare their distribution in global color to the distribution of pure disk (late-type) galaxies in Fig. 1. The type of bulge a galaxy has is a signpost for an evolutionary history of the total galaxy.

Thus, the location of a galaxy with respect to the bimodality does – at least in part – reflect differing evolutionary paths of the whole galactic system. It is not merely a reflection of different emphasis of the disk and bulge subcomponents.

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