Constraining Galaxy Evolution With Bulge-Disk-Bar Decomposition

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Abstract.

Structural decomposition of galaxies into bulge, disk, and bar components is important to address a number of scientific problems. Measuring bulge, disk, and bar structural parameters will set constraints on the violent and secular processes of galaxy assembly and recurrent bar formation and dissolution models. It can also help to quantify the fraction and properties of bulgeless galaxies (those systems having no bulge or only a relatively insignificant disky-pseudobulges), which defy galaxy formation paradigms requiring almost every disk galaxy to have a classical bulge at its core.

We demonstrate a proof of concept and show early results of our ongoing three-component bulge-disk-bar decomposition of NIR images for a sample of three complementary samples spanning different epochs and different environments (field and cluster). In contrast to most early studies, which only attempt two-component bulge-disk decomposition, we fit three components using GALFIT: a bulge, a disk, and a bar. We show that it is important to include the bar component, as this can significantly lower the bulge-to-total luminosity ratio ($B/T$), in many cases by a factor of two or more, thus effectively changing the Hubble type of a galaxy from early to late.

1. Introduction

The formation of galaxies is a classic problem in astrophysics. Contemporary galaxy formation models combine the well-established Lambda-Cold Dark Matter (LCDM) cosmology, which describes behavior of dark matter on very large scales, with baryonic physics to model galaxy formation. In the early Universe, pockets of dark matter decoupled from the Hubble flow, collapsed into virialized halos, and then clustered hierarchically into larger structures. Meanwhile, gas aggregated in the interiors of the halos to form rotating disks, which are the building blocks of galaxies (Navarro & Steinmetz, 2002; Cole et al. 2000). Such disks were destroyed during mergers of their parent halos, leaving behind classical de Vaucouleurs bulges. Spiral disk galaxies formed subsequently as gaseous disks accreted around spheroids (Burkert & Naab, 2004).

Troubling inconsistencies exist between real galaxies and LCDM models of galaxy formation. One issue is the angular momentum problem; simulated galaxy disks have smaller scalelengths and, therefore, less specific angular momentum than their counterparts in nature (D’Onghia & Burkert, 2006). A second problem is the severe under prediction in the fraction of galaxies with low bulge-to-total mass ratio ($B/T < 0.2$) and of so-called bulgeless galaxies, which lack a classical bulge. Simulated spiral galaxies feature prominent classical bulges in their cores. Such predictions are in glaring contradiction with emerging observations that suggest 15-20% of disk galaxies out to $z \sim 0.3$ are bulgeless (Kautsch et al. 2006; Barazza et al. 2007).

There are many unanswered questions about the assembly of bulges, the distribution of $B/T$, and the properties of so-called bulgeless galaxies with low $B/T$. How do

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properties, such as disk scalelengths, mass, kinematics, colors, and star formation histories vary across galaxies of different \( B/T \), ranging from bulge-dominated systems to quasi-bulgeless systems? Are quasi-bulgeless systems confined to low mass systems with high specific star formation rates, while classical bulges populate high mass systems? How do the fraction, mass function, and structural properties of galaxies with different \( B/T \) vary across environments with different large-scale cosmological overdensities? If environment plays a central part in suppressing bulge formation, then differences would be expected in the properties of bulgeless galaxies in different environments, such as field versus dense galaxy clusters. How does the frequency and properties of galaxies with low \( B/T \) as a function of redshift over \( z = 0.2 - 0.8 \) compare to the recently reported merger history of galaxies over this epoch (Jogee et al 2007)? Answering these questions will help us to understand the reasons behind the apparent failure of LCDM galaxy formation models, and shed light on how galaxies assemble.

Progress is possible by observationally constraining properties of enigmatic bulgeless galaxies. A powerful technique for measuring the structural properties (e.g. scalelengths, Sérsic indexes, \( B/T \)) of galaxies is the decomposition of the 2D light distribution into separate structural components with GALFIT (Peng et al. 2002). Most earlier work has only performed 2D bulge-disk decomposition, but because late-type spirals have been shown to have higher optical bar fractions than early-type galaxies (Barazza et al. 2007), it is important to include the bar when analyzing disk-dominated systems. Bars can contain a significant fraction of light, so failure to account for bars could lead to inflated \( B/T \) (Laurikainen et al. 2006).

2. Methodology and Samples

We perform three-component decomposition of the 2D galaxy light distribution, while taking the PSF into account, with GALFIT. Since GALFIT utilizes a non-linear least squares algorithm, initial guess parameters are required for each component GALFIT attempts to fit. While reasonable initial guesses can be generated by inspection in many cases with common tools (e.g. IRAF), this is time-consuming and inefficient for large samples. In practice, we break three-component decomposition into three separate invocations of GALFIT.

We first perform one and two-component fits to constrain the bulge and disk parameters. The single-component fit models the entire galaxy with only a Sérsic bulge component. In addition to constraining the bulge structural parameters, the total luminosity of the object is also determined.

A two-component fit, consisting of a Sérsic bulge and exponential disk, is then made based on the output of the previous fit. If GALFIT is allowed to do an unconstrained two-component bulge-disk fit in a strongly barred galaxy, it will often try to fit the bar by artificially stretching the disk along the bar PA. In order to get physically meaningful two-component fits, we therefore constrain the fit by fixing the position angle and axis ratio (b/a) of the outer disk to values pre-determined by fitting an ellipse to the outermost disk isophote.

Finally, a three-component bulge-bar-disk fit is performed, using the two-component fits as initial guesses for the bulge parameters, and fixing the disk b/a and PA as before. Bars are modeled with elongated, low-index Sérsic components using initial guesses for the size and position angle estimated from the images. All objects are subjected to the three-component fits, regardless of whether they appear by eye to possess a bar. If there is independent evidence for an AGN or nuclear cluster, a point source is fitted as a fourth component.

In order to decide which of the two or three-component fit is better, a number of criteria are used. 1) If the one or two-component residuals show a bar signature that is removed in the three-component residual, then the three component fit is favored; 2) Structural parameters (scalelength, Sérsic index, b/a) of the bar fit must well behaved;
3) Visual evidence of a strong bar in the input images favors the three-component fit. Weak bars are often not visually prominent, but for such bars, the changes in the disk or bulge parameters, between the two and three component fits, are small; (4) In addition, we test the robustness of the three-component solution by varying the initial guesses to check that the same solution is converged upon.

In order to address the questions outlined in §1, we are applying the three-component decomposition to three complementary samples, which span different epochs and different environments (field and cluster): (1) a $z \sim 0$ sample of $\sim 200$ galaxies with Hubble types S0 to Sm drawn from the OSU Bright Spiral Galaxy Survey (OSUBSG) (Eskridge et al. 2002) and UKIDSS (McLure et al. 2006); (2) a sample of galaxies in the dense environment of the Coma cluster from our ACS Treasury survey (Carter et al 2007); and a sample of early disk galaxies out $z \sim 2$ with deep NICMOS imaging (180 orbits).

3. Preliminary Findings

For the two-component fits, we have performed consistency checks by testing our decomposition on samples of galaxies with published results from the Millennium Galaxy Catalog (Driver et al. 2007) and the New York University Value-Added Catalog (Blanton et al. 2005) for the Sloan Digital Sky Survey.

For three-component fits, we have performed similar tests on a few galaxies drawn from small samples with published three-component bulge-bar-disk fits, drawn from Laurikainen et al. (2006) and Reese et al. (2007).

An example of our method is presented in Figure 1, which illustrates the complete three-step decomposition for NGC 4643. We now summarize our preliminary findings:

1. Luminosity is conserved between the two and three-component fits.

2. Modeling the bar in the three-component fits forces a reshuffling of luminosity. Generally, the bulge declines in luminosity, whereas light can be taken from, or added back, to the disk. The reshuffling of light occurs because the two-component model adjusts the bulge and disk accordingly to compensate for the bar, which can include artificially elongating and brightening the bulge. Accounting for the bar returns the bulge and disk parameters closer to their true values.

3. Inclusion of the bar can reduce bulge fractional luminosity $B/T$ by a factor of two or more. Larger changes in bulge luminosities (a factor of 10 or more) occur in cases where a prominent bar influences the two-component fit to very much overstate the bulge luminosity. The bulge-disk fits in such extreme cases underscore the importance of including the bar in 2D luminosity decomposition.

4. The scalelength of the disk is generally unchanged by including the bar. However in a few cases, the two-component disk structure can be erroneous, as in the case of NGC 4643, shown in Figure 1.

We have provided a proof of concept of our ongoing three-component bulge-disk-bar decomposition with GALFIT. We are optimistic about our on-going work, which will be described in Weinzirl et al. 2008 (in prep).

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Figure 1. Shown is the complete three-step decomposition for NGC 4643. From top to bottom, the rows show the fits from the one, two, and three-component decompositions. The residuals for the one and two-component fit show a distinct bar signature. In Step 2, the fitted disk has an unphysically large scalelength (335″) that does not match the galaxy. Due to its resulting low surface brightness, the fitted disk is hard to see, and ellipses are drawn to show its PA and b/a. In Step 3, the addition of the bar component restores the disk scalelength to a reasonable value. The fit parameters are presented in Table 1.

| Fit   | r_e or h (″) | n  | b/a | Position Angle | Fractional light |
|-------|-------------|----|-----|----------------|------------------|
| Step 1 Sersic | 27.90 | 4.44 | 0.80 | -51.08         | 100%             |
| Step 2 Bulge   | 23.86 | 4.16 | 0.80 | -51.08         | 34.6%            |
| Disk          | 335.88 | 1.0  | 0.84 | 66.94          | 65.4%            |
| Step 3 Bulge   | 5.43  | 2.53 | 0.90 | 60.52          | 25.0 %           |
| Disk          | 48.22 | 1.0  | 0.84 | 66.94          | 54.1 %           |
| Bar           | 21.30 | 0.62 | 0.37 | -45.84         | 20.9 %           |

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