Research Statement (Shardha Jogee)

Over the period 2004–2008, my research group at UT Austin has included three beginning graduate students (A. Heiderman, T. Weinzirl, I. Marinova), two undergraduate Dean scholars (S. Miller and K. Penner), and postdoctoral fellow F. Barazza. Below is a description of my research program and the questions we are addressing.

1. Overview

Contemporary galaxy formation models combine the well-established Λ Cold Dark Matter (ΛCDM) cosmology, which describes behavior of dark matter on very large scales, with baryonic physics to provide a general framework for galaxy evolution (e.g., Somerville & Primack 1999; Somerville et al. 2008; Cole et al. 2000; Steinmetz & Navarro 2002; White et al. 2004; Springel et al 2005a,b; Springel & Hernquist 2005; Khochfar & Burkert 2005; Maller et al. 2006) The predictions on how galaxies evolve are not unique or robust as they depend sensitively on the merger history of galaxies in the models, (which is much less well determined than the merger rates of isolated dark matter halos), the baryonic physics (e.g., gas cooling, star formation (SF), and feedback from supernovae and AGN), and to some extent on the resolution of numerical resolutions (e.g., Mayer et al. 2008). Furthermore, several areas of discord with observations have been claimed, such as the angular momentum problem (Navarro & Steinmetz 2000; Burkert & D'Onghia 2004; D'Onghia et al. 2006), the sub-structure problem, and the problem of bulgeless galaxies.

In order to glean direct insight into galaxy evolution, as well as test current models, my research program endeavors to set empirical constraints on the merger history, SF, and structural components (e.g., bars and bulges) of galaxies at different redshifts and in different environments. Furthermore, we are also attempting to shed light on the relative importance of evolution driven by secular processes, major mergers and minor mergers over the last 10 Gyr (§ 2 to 4). One of the driving philosophy behind my work is that I believe in the need for close collaborations between observers and theorists: thus, in most of my papers (e.g., Jogee et al. 1999, 2002a, 2002b, 2004, 2005, 2008; Berentzen, Shlosman, & Jogee 2006; Heiderman, Jogee, et al. 2008; Weinzirl, Jogee, Khochfar, Burkert, & Kormendy 2008, hereafter WJKBK08), I perform detailed comparisons with theoretical models or/and work closely with theorists in order to advance the concurrent development of the theoretical framework.

Many of my scientific projects are enabled by large multi-wavelength galaxy surveys to which I am fortunate to have access, as a team member of five science collaborations, namely GEMS (Rix et al. 2004; http://www.mpia.de/GEMS/gems.htm); ACS-GOODS (Giavalisco et al 2004); Space Telescope Abell 901/902 Survey (STAGES; Gray et al. 2008), the Coma Cluster HST ACS Treasury Survey (Carter et al. 2008); and NICMOS-GOODS (Conselice et al 2008, in prep.). As questions are often raised on the role of members within large collaborations, I would like to specify that my research group at UT and I are leading the science on barred galaxies in the GEMS, STAGES, Coma, and NICMOS-GOODS collaborations, and leading some of the papers on the history and impact of galaxy interactions in the GEMS, STAGES, and Coma collaborations.

2. Bars and their impact on galaxy evolution

(A1) Bars and their impact on the inner kpc of local nearby galaxies: Stellar bars are recognized as the most important *internal* factor that redistributes the angular momentum of the baryonic and dark matter components of disk galaxies, thereby driving their dynamical and secular evolution. My early work (1998 to 2002) focused on understanding the gas inflow driven by primary and nuclear stellar bars, and the subsequent evolution of the circumnuclear region, through high resolution radio interferometric observations of the molecular gas, modeling, and complementary optical and NIR observations. These high resolution ($\sim 1''$ to $2''$ corresponding to 100–200 pc at a distance of 20 Mpc) radio interferometric observations, conducted with the Caltech OVRO mm array, are *extremely time-intensive*: typical time allocations allowed 1 or 2 galaxies to be done each year, and it takes six months to cycle through the different array configurations (C, L, H, U) needed to make a final data cube for one object. Thus, my early studies focused on individual systems, such as NGC 2782, NGC 4102, and NGC 5248 where I studied starbursts and their outflows (Jogee et al. 1998; 2003a), evolution driven by nuclear stellar bars (Jogee et al. 1999) and large-scale primary bars (Jogee et al. 2002a), and bar-driven fueling of a circumnuclear starburst ring of super-star clusters (Jogee et al. 2002b; 2003b).

Finally, putting together interferometric C0 observations collected over nine years for ten galaxies, we presented one of the largest high-resolution (150-250 pc) study of molecular gas and SF in the inner kpc of barred galaxies (Jogee, Scoville, & Kenney 2005). Our main results were as follows. (1) We showed that the inner kpc of bars differs markedly from the outer disk, hosting molecular gas surface densities of 500-3500 $M_\odot$ pc^{-2}, gas mass fractions of 10% to 30%, gas velocity dispersions of 10 to 40 km s^{-1}, and epicyclic frequencies of several 100–1000 km s^{-1} kpc^{-1}. In this environment, gravitational instabilities set in only at very high gas densities (few 100-1000 $M_\odot$ pc^{-2}), but once triggered, they grow rapidly on a timescale of a few Myrs. This high density, short timescale, 'burst ' mode may explain why the most intense starbursts tend to be in the central parts of galaxies. (2) We explored why galaxies with similar amount of molecular gas in the inner few kpc, display an order of magnitude variation in their SFR per unit molecular gas (SFR/$M_{\rm H2}$). We found two classes of systems that display low (SFR/$M_{\rm H2}$). The first class includes galaxies in the early stages of bar-driven gas inflow, where a lot of the circumnuclear gas is along the stellar bar, has large non-circular kinematics and experiences a large shear: this gas does not form stars efficiently. The second class includes galaxies that seem to be at a later stage of bar-driven gas inflow: most of the circumnuclear molecular gas is now in the inner kpc of the bar, inside its outer inner Lindbald resonance (OILR), and shows predominantly circular motions, but its surface density appears to be significantly below the Toomre critical density. In contrast, 'starbursts' or systems with high (SFR/$M_{\rm H2}$) tend to have larger gas surface densities, which are closer to the Toomre critical density over a larger region. In fact, the Toomre Q parameter reaches its minimum value in the region of SF, despite an order of magnitude variation in the gas surface density and epicyclic frequency. This suggests that the onset of gravitational instabilities, as characterized by Q, may play an important role even in the inner kpc region. (3) We investigated the distribution of molecular gas w.r.t. the dynamical resonances of the large-scale stellar bar and estimate upper limits in the range 43 to 115 km s^{-1} kpc^{-1} for the bar pattern speed and an OILR radius of $>$ 500 pc. (4) We also show evidence of disky high V/σ stellar components (so-called pseudobulges) inside the OILR of the large-scale bar, and suggest that recurrent bar-driven gas inflow and circumnuclear starbursts can contribute to the gradual buildup of such systems.

(A2) Bars as a function of redshift in the cosmological context: While the above high resolution radio interferometric studies of a small sample of nearby barred galaxies afforded important insights, and set the stage for future ALMA studies, there was a pressing need to put primary stellar bars[1] in a cosmological context and explore how their properties evolve with redshift and environment. Early Hubble Deep Field WFPC2 studies (e.g., Abraham et al 1999) sampled very small volumes, while the coarse PSF of NIC3-based studies allowed only the largest bars to be detected out to $z \sim 1$ (e.g., Sheth et al 2003). But, with the advent of large galaxy surveys conducted with the Advanced Camera for Surveys (ACS) aboard the *Hubble Space Telescope* (*HST*) as of 2003, we now had high resolution, sensitive observations of large galaxy samples to attack the problem.

One hurdle was that widely used methods to identify and characterize primary bars, such as Fourier techniques (e.g., Buta et al. 2003; 2005) and ellipse-fitting (e.g., Knapen et al. 2000; Laine et al. 2002; Jogee et al. 1999; 2002a) had only been used for manual fits of small samples of 70 to 120 galaxies, as of 2004. I therefore invested significant time in developing a bar analysis package (Jogee et al. 2004) consisting of the following: (1) An iterative adaptive tool that automates the process of ellipse-fits such that a given fit adaptively 'learns' from previous fits; (2) An interactive analysis tool, where one can inspect the fitted ellipses overlaid on galaxy images, and then apply quantitative criteria to the radial profiles of ellipticity, PA, and surface brightness from ellipse fits, in order to identify and characterize the properties of primary bars and disks (ellipticity e, semi major axis a, PA, etc). These quantitative criteria are based on simulations of stellar orbits and shock loci in barred potentials.

This bar analysis package and the approach established in Jogee et al. (2004) has been *instrumental* in allowing my research group and me to perform bar analyses in samples, *which are a factor of 10 to 20 times larger* than previously done: these include 1590 galaxies out to $z \sim 1$ in the GEMS survey (Jogee et al 2004); 260 optical and NIR images in the OSU survey of local bright spirals (Marinova & Jogee 2007); 2000 late-type SDSS disk galaxies at $0.01 \leq z < 0.03$ (Barazza, Jogee, Marinova 2008a, hereafter BJM08a); 800 bright galaxies in the STAGES A901/902 supercluster survey at $z \sim 0.17$ (Marinova, Jogee, & the STAGES collaboration 2008); 500 galaxies in the ACS treasury survey of the Coma cluster at $z \sim 0.025$ (Weinzirl, Jogee, & the Coma collaboration, in prep.), and 2256 disk galaxies in the EDisCS survey (White et al. 2005) of clusters at $z \sim 0.4$–1.0 (Barazza, Jablonka, Desai, Jogee & the EDisCS collaboration 2008b).

In the first paper (Jogee et al 2004), we ellipse-fitted and analyzed 1590 galaxies over $z \sim 0.2$–1.0 drawn from 1/4 of the GEMS survey. Both F606W and F850LP images were analyzed in order to minimize shifts in the rest-frame bandpass. It is worth noting that this sample was 10 times larger than any other sample used for bar studies at the time. Three different techniques (based on Sérsic cuts, rest-frame color cuts, and concentration indices) commonly used at intermediate

[1]Primary bars, also called large-scale bars, typically have semi-major axis $a \geq 1.5$ kpc in bright massive spirals of Hubble types S0 to Sc, while secondary (nuclear) bars typically have $a < 1.0$ kpc (Laine et al. 2002; Erwin & Sparke 2002). The studies described in § A2 only focus on characterizing primary bars at intermediate redshifts.

redshifts to identify disks were applied in order to derive the optical bar fraction (Fig. 1a). This allowed uncertainties caused by the selection of disk galaxies to be characterized. After applying inclination and absolute magnitude cuts, we found from the resulting sample of $\sim$ 255 bright spiral galaxies that the observed optical fraction of *strong (ellipticity* $e \geq 0.4$*)* bars remains fairly constant, ranging from ($36\% \pm 6\%$) over $z \sim$ 0.2–0.7, to ($24\% \pm 4\%$) over $z \sim$ 0.7–1.0 (see Table 1 in Jogee et al. 2004). The results are shown on Fig. 1a. In particular, we do not find a dramatic order of magnitude decline in the fraction of strong ($e \geq 0.4$) bars suggested by the earlier study of Abraham et al. (1999): their Figure 4 shows that the fraction of strong bars with $e \geq 0.4$ (corresponding to $(b/a)^2 \leq 0.36$ on their Fig. 4) falls from 9/31 ($29\% \pm 10\%$) over $z \sim$ 0.2–0.7 to 0% at $z \sim$ 0.7–1.0. In contrast, our results on Fig. 1a only allow for a modest factor of $\sim$ 1.5 to 2 decline in the *observed* optical fraction of strong bars over $z \sim$ 0.2–1.0 *before* correcting for the artificial loss of bars by redshift-dependent systematic effects. In effect, our results *rule out an order of magnitude decline in the fraction of strong bars over* $z \sim$ *0.2 to 1.0*: *they suggest that strong bars are frequent over the last 8 Gyr, an interval long enough for bars to drive significant evolution.*

It is important to note that our study considered only *strong (*$e \geq$ *0.4)* bars. This choice was motivated by the fact that strong ($e \geq 0.4$) bars have a larger impact on galaxy evolution, and can be more robustly traced over $z \sim$ 0.2 to 1.0 than weak bars with ellipticity e between 0.25 to 0.40. It is encouraging to see on Fig. 1a that our results from GEMS on the *observed* optical fraction of *strong (*$e \geq$ *0.4)* bars over $z \sim$ 0.2 to 1.0 (Jogee et al. 2004) are consistent with those reported later from a much larger sample of 2000 spirals (Sheth et al. 2008) in the COSMOS survey (although their interpretation of the results differ). In contrast, the empirical results from studies that considered all *(i.e strong+weak)* bars tend to show more divergence even at $z < 0.7$, as shown in Fig. 1b.

We complemented the GEMS study over $z \sim$ 0.2 to 1.0 (Jogee et al 2004) with two studies focusing on bars at $z \sim 0$ (Marinova & Jogee 2007) and at $0.01 \leq z < 0.03$ (BJM08a), in order to nail down the rest-frame optical 'zero-redshift' point for bars (see § A3). Based on these three studies, our interpretation is that a large part, if not all, of the decline in the *observed* optical fraction of *strong (*$e \geq$ *0.4)* bars over $z \sim$ 0,2–1.0 is due to an artificial loss of bars caused by two redshift-dependent systematic effects: the decreasing spatial resolution and the increasing obscuration of bars by SF and dust as the redshift rises from 0.2 to 1.0. Locally, primary stellar bars typically have semi-major axis $a \geq 1.5$ kpc, and the majority of them have $a \leq 5$ kpc (Marinova & Jogee 2007; BJM08a). Only bars with $a \geq 2.5$ times the PSF can be robustly characterized using ellipse-fitting and our quantitative criteria for bar detection (Jogee et al. 2004), since we need to sample the bulge region, several points along the smoothly rising e and PA plateau over the bar length, and the transition to the disk. Thus, primary bars with $a > 1.5$ kpc require a minimum PSF of 600 pc for robust characterization. Since the ACS PSF ($0.1''$ in drizzled frames) drops from 300 to 800 pc from $z \sim 0.2$ to 1.0, we expect to increasingly lose bars with a in the range of 1.5 to 2.0 kpc at $z > 0.5$ (Fig. 1c). The decreasing spatial resolution alone can cause the optical bar fraction to artificially drop by a factor of 1.3 by $z \sim 1$ (e.g., Marinova & Jogee 2007; BJM08a). The second pernicious systematic effect is that the obscuration of bars by SF and dust can mask bars at optical wavelengths: even at $z \sim 0$ this effect already causes a factor of 1.3 loss in optically-visible bars (Marinova & Jogee 2007), and this loss factor X is very likely to rise with z over the interval $z \sim 0$ to 1.0, where the SFR density rises by a factor of 4 to 10 (e.g., Lilly et al .1996; Le Floc'h et al. 2005; Jogee et al. 2008; Fig. 2d). The amount by which X rises with z is presently unknown and constitutes the largest uncertainty. Thus, after taking into account systematic effects, our results allow for three possibilities, depending on how much the bar loss factor X due to obscuration by SF and dust rises with redshift: a slightly declining, a constant, or a rising bar fraction with redshift out to $z \sim 1$. In order to constrain X and help distinguish between the three possibilities, we need future work in the rest-frame NIR with WFC3 and JWST so as to trace optically-obscured bars of intermediate size (Fig. 1d).

(A3) Establishing the $z \sim 0$ point for bars in the field: We complemented the GEMS study over $z \sim 0.2$ to 1.0 (Jogee et al 2004) with two studies focusing on bars at $z \sim 0$ in order to nail down the rest-frame optical 'zero-redshift' point for bars. We first established the $z \sim 0$ reference baseline point in the rest-frame B and H bands, using 180 spirals of intermediate Hubble types (Marinova & Jogee 2007) in the OSU survey of bright spirals. We found that the bar fraction is $\sim 44\%$ in the rest-frame B-band, where dust and SF obscure about 1/3 of the bars visible in the NIR. After applying to the OSU data, the same cutoffs in magnitude, bar size, and bar ellipticity ($e_{\rm bar} \geq 0.4$), which are relevant for strong bars out to $z \sim 1$ in the GEMS survey, we find that the decreasing spatial resolution would cause the optical B-band bar fraction to fall from 44% at $z \sim 0$, to $\sim 34\%$ by $z \sim 1$ (Marinova & Jogee 2007). Allowing for a rising obscuration of bars by SF and dust with redshift, can further lower this fraction significantly. Thus, the observed decline in the optical bar fraction from $36\% \pm 6\%$ to $24\% \pm 4\%$ over $z \sim 0.2$ to 1.0 in GEMS (Jogee et al. 2004) may in large part be due to redshift-dependent systematic effects.

A similar result is obtained by BJM08a, where ~ 2000 disk galaxies in SDSS at $0.01 \leq z < 0.03$ were analyzed using the bar analysis package and quantitative criteria established in (Jogee et al 2004). This study complemented Marinova & Jogee (2007) by extending the analyses to the rest-frame r-band and to spirals of lower luminosities and later Hubble types. Interestingly we found that disk-dominated galaxies with no bulge or a very low B/D display a significantly higher optical bar fraction ($> 70\%$ vs 40%) than galaxies with prominent bulges. Furthermore, our study finds that $\sim 20\%$ of disk galaxies appear to be "quasi-bulgeless", presenting a potential challenge to ΛCDM models (see also § 4).

(A4) Bars as a function of environment: While bars in the field have been widely studied, comparatively little is known about the frequency, properties, and impact of bars in rich clusters (e.g., van den Bergh 2002; Mendez-Abreu, Aguerri, & Corsini 2008). Not only do clusters provide an interesting laboratory to test bar formation models, but bars can also be used to test the mode of cluster growth. Using the bar analysis package and quantitative approach established in Jogee et al (2004), we are currently exploring bars in clusters through three studies: a study of 800 bright galaxies in the STAGES A901/902 supercluster survey at $z \sim 0.17$ (Marinova, Jogee, & the STAGES collaboration 2008); a study of 500 galaxies in the ACS treasury survey of the rich Coma cluster at $z \sim 0.025$ (Weinzirl, Jogee, & the Coma collaboration, in prep.); and a study of 2256 disk galaxies in the EDisCS survey of clusters at $z \sim 0.4$–1.0 (Barazza, Jablonka, Desai, Jogee & the EDisCS collaboration 2008b).

Our early results from the STAGES survey suggest that the optical bar fraction in the rich A901 and A902 clusters is similar to that of the field, and shows no significant trend with any local environment tracer, such as the projected mass density κ, Σ_{10}, ICM density from X-ray emission, and the projected distance to the nearest cluster center (Marinova, Jogee, & the STAGES collaboration 2008). Similarly, no significant difference is found between the optical bar fraction of field and clusters over $z \sim$ 0.4–1.0 in the EDisCS survey (Barazza et al 2008b). The latter study also finds no evidence for any strong decline in the optical bar fraction with redshift. Taken together, our results increasingly suggest that the processes controlling the frequency and properties of bars are not a strong function of environment.

3. History of Galaxy Interactions and their Impact on SF over the Last 7 Gyr

The merger history of galaxies impacts the mass assembly (e.g., Dickinson et al. 2003), star formation history, AGN activity (e.g., Springel. et al. 2005b) and structural evolution of galaxies. The merger rate/fraction at $z > 1$ remains highly uncertain, owing to relatively modest volumes and bandpass shifting effects, but with a general trend towards higher merger fractions at higher redshifts Even the merger rate at $z < 1$ has proved hard to robustly measure for a variety of reasons, ranging from small samples in early studies, to different methods on large samples in later studies.

In Jogee et al. (2008a,b), we have performed a complementary and comprehensive observational estimate of the frequency of interacting galaxies over $z \sim$ 0.24–0.80 (lookback times of 3–7 Gyr), and the impact of interactions on the SF of galaxies over this interval. Our study is based on *HST* ACS, COMBO-17, and Spitzer 24 μm data from the GEMS survey. We use a large sample of $\sim$ 3600 ($M \geq 1 \times 10^9$ $M_\odot$) galaxies and $\sim$ 790 high mass ($M \geq 2.5 \times 10^{10}$ $M_\odot$) galaxies for robust number statistics. Two independent methods are used to identify strongly interacting galaxies: a tailored visual classification system complemented with spectrophotometric redshifts and stellar masses, as well as the CAS merger criterion ($A > 0.35$ and $A > S$; Conselice 2003). While many earlier studies focused only on major mergers, we try to constrain the frequency of minor mergers as well, since they dominate the merger rates in ΛCDM models. Some of our results are outlined below.

Among $\sim$ 790 high mass galaxies, *the fraction of visually-classified interacting systems over lookback times of 3–7 Gyr ranges from 9% ± 5% at $z \sim$ 0.24–0.34, to 8% ± 2% at $z \sim$ 0.60–0.80, as averaged over every Gyr bin.(Fig. 2a).* These systems appear to be in merging or post-merger phases, and are candidates for a recent merger of mass ratio $M1/M2 > 1/10$. The lower limit on the major ($M1/M2 > 1/4$) merger fraction ranges from 1.1% to 3.5% over $z \sim$ 0.24–0.80. The corresponding lower limit on the minor ($1/10 \leq M1/M2 < 1/4$) merger fraction ranges from 3.6% to 7.5%. This is the first, albeit approximate, empirical estimate of the frequency of minor mergers over the last 7 Gyr.

For an assumed value of $\sim$ 0.5 Gyr for the visibility timescale, it follows that *each massive ($M \geq 2.5 \times 10^{10}$ $M_\odot$) galaxy has undergone $\sim$ 0.7 mergers of mass ratio > 1/10 over the redshift interval $z \sim$ 0.24–0.80. Of these, we estimate that 1/4 are major mergers, 2/3 are minor mergers, and the rest are ambiguous cases of major or minor mergers.* The corresponding merger rate R is a few $\times 10^{-4}$ galaxies Gyr^{-1} Mpc^{-3}. Among $\sim$ 2840 blue cloud galaxies of mass $M \geq 1.0 \times 10^9$ $M_\odot$, similar results hold.

We compare our empirical merger rate R for high mass ($M \geq 2.5 \times 10^{10}\ M_\odot$) galaxies to predictions from different ΛCDM-based simulations of galaxy evolution, including the halo occupation distribution (HOD) models of Hopkins et al. (2007); semi-analytic models (SAMs) of Somerville et al. (2008), Bower et al. (2006), and Khochfar & Silk (2006); and smoothed particle hydrodynamics (SPH) cosmological simulations from Maller et al. (2006). To our knowledge, such extensive comparisons have not been attempted to date, and are long overdue. *We find qualitative agreement between the observations and models, with the (major+minor) merger rate from different models bracketing the observed rate, and showing a factor of five dispersion (Fig. 2b).* One can now anticipate that in the near future, improvements in both the observational estimates and model predictions will start to rule out certain merger scenarios and refine our understanding of the merger history of galaxies.

The idea that galaxy interactions generally enhance the SFR of galaxies is well established from observations (e.g., Joseph & Wright 1985; Kennicutt et al. 1987) and simulations (e.g., Hernquist 1989; Mihos & Hernquist 1994, 1996; Springel, Di Matteo & Hernquist 2005b). However, simulations cannot uniquely predict the factor by which interaction enhance the SF activity of galaxies over the last 7 Gyr, since both the SFR and properties of the remnants in simulations are highly sensitive to the stellar feedback model, the bulge-to-disk (B/D) ratio, the gas mass fractions, and orbital geometry (e.g., Cox et al 2006; di Matteo et al. 2007). Thus, empirical constraints are needed. Among $\sim$ 3600 intermediate mass ($M \geq 1.0 \times 10^9\ M_\odot$) galaxies, we find that *the average SFR of visibly interacting galaxies is only modestly enhanced compared to non-interacting galaxies over $z \sim$ 0.24–0.80 (Fig. 2c).* This result is found for SFRs based on UV, UV+IR, and UV+stacked-IR data. This modest enhancement is consistent with the results of di Matteo et al. (2007) based on numerical simulations of several hundred galaxy collisions.

The SF properties of interacting and non-interacting galaxies since $z < 1$ are of great astrophysical interest, given that the cosmic SFR density is claimed to decline by a factor of 4 to 10 since $z \sim 1$ (e.g., Lilly et al. 1996; Ellis et al 1996; Hopkins 2004; Pérez-González et al. 2005; Le Floc'h et al. 2005). We therefore set quantitative limits on the contribution of obviously interacting systems to the UV-based and UV+IR-based SFR density over $z \sim$ 0.24–0.80. Among $\sim$ 3600 intermediate mass ($M \geq 1.0 \times 10^9\ M_\odot$) galaxies, we find that *visibly interacting systems only account for a small fraction (< 30%) of the cosmic SFR density over lookback times of $\sim$ 3–7 Gyr ($z \sim$ 0.24–0.80; Fig. (2d)).* Our result is consistent with that of Wolf et al. (2005) over a smaller lookback time interval of $\sim$ 6.2–6.8 Gyr. In effect, our result suggests that *the behavior of the cosmic SFR density over the last 7 Gyr is predominantly shaped by non-interacting galaxies, rather than strongly interacting galaxies.* This suggests that the observed decline in the cosmic SFR density since $z \sim 0.80$ is largely the result of a shutdown in the SF of non-interacting galaxies.

4. The origin of bulges and the problem of bulgeless galaxies

In ΛCDM models of galaxy evolution, there are in principle three main mechanisms to build bulges of spiral galaxies: major mergers, minor mergers, and secular processes (see WJKBK08 for details). The major merger of two spiral galaxies destroys the disk component and leaves behind a classical bulge, around which a stellar disk forms when hot gas in the halo subsequently cools, settles into a disk, and forms stars. Minor mergers can also grow bulges in several ways. A tidally induced bar and/or direct tidal torques from the companion can drive gas into the inner kpc (e.g., Quinn et al. 1993; Hernquist & Mihos 1995; Jogee 2006 and references therein), where subsequent SF forms a compact high v/σ stellar component, or disky pseudobulge. In addition, the stellar core of the satellite can sink to the central region via dynamical friction. Finally, bulges can also have a secular origin: here, a stellar bar or globally oval structure in a *non-interacting* galaxy drives gas inflow into the inner kpc , where subsequent SF forms a disky pseudobulge (e.g., Kormendy 1993; Jogee 1999; Kormendy & Kennicutt 2004; Jogee, Scoville, & Kenney 2005).

These different mechanisms to form bulges have been postulated for a long time. However, what is still missing is *a quantitative assessment of the relative importance of different bulge formation pathways* in high and low mass spirals. For instance, although bulges are an integral part of massive present-day spiral galaxies, we still cannot answer the following basic question: do most bulges in massive spirals form via major mergers, minor mergers, or secular processes?

Another thorny issue is the prevalence of bulgeless galaxies. There is rising evidence that bulgeless galaxies are quite common in the local Universe (e.g., Böker et al. 2002; Kautsch et al. 2006; BJM08a; Kormendy & Fisher 2008). Yet, in ΛCDM models of galaxy evolution, most galaxies that had a past major merger at a time when their mass was a fairly large fraction of their present-day mass, are expected to have a significant bulge. So far, no quantitative comparisons have been done between observations and model predictions to assess how serious is the challenge posed by bulgeless galaxies.

In WJKBK08, we attempt one of the first quantitative comparisons of the properties of bulges in a fairly complete sample of high mass ($M_\star \geq 1.0 \times 10^{10} M_\odot$) spirals to predictions from ΛCDM-based simulations of galaxy evolution. We derive the bulge-to-total mass ratio (B/T) and bulge Sérsic index n by performing $2D$ bulge-disk-bar decomposition on H-band images of 146 bright, high mass, moderately inclined spirals. Interestingly, we find that as many as $\sim 56\%$ of high mass spirals have low $n \leq 2$ bulges: such bulges exist in barred and unbarred galaxies across all Hubble types (Fig. 3a). Furthermore a striking $\sim 66\%$ of high mass spirals have $B/T \leq 0.2$ (Figs. 3a and 3b).

We compare the observed distribution of bulge B/T in high mass spirals to predictions from ΛCDM-based semi-analytical models. In the models, a bulge with $B/T \leq 0.2$ can exist in a galaxy with a past major merger, only if the last major merger occurred at $z > 2$ (lookback > 10 Gyr). The predicted fraction of high mass spirals with a past major merger and a bulge with a present-day $B/T \leq 0.2$ is *a factor of over fifteen smaller* than the observed fraction ($\sim 66\%$) of high mass spirals with $B/T \leq 0.2$. The comparisons *rule out major mergers as the main formation pathway for bulges in high mass spirals.* Contrary to common perception, *bulges built via major mergers seriously fail to account for the bulges present in $\sim$ 66% of high mass spirals.*

In the models, the majority of low $B/T \leq 0.2$ bulges exist in systems that have experienced *only minor mergers, and no major mergers.* These bulges can be built via minor mergers and secular processes. So far, we explored one realization of the model focusing on bulges built via satellite stars in minor mergers and find good agreement with the observations. Future models will explore more realistic minor merger scenarios and secular processes in paper II.

5. Future Directions

I plan to probe the early stages of galaxy evolution, out to epochs when the Universe was less than 1 Gyr old, using upcoming future facilities, such as WFPC3 on the Hubble Space Telescope, the James Webb Space Telescope (JWST), the Giant Magellan Telescope (GMT), the Atacama Large Millimeter array (ALMA) and potentially the Cornell Caltech Atacama submillimeter Telescope (CCAT).

To date, the large galaxy surveys conducted with the Advanced Camera for Surveys (ACS) aboard the Hubble can trace the rest-frame optical light and intermediate age stellar populations only out to $z \sim 1$, corresponding to half the age of the Universe. At higher redshifts, these observations only probe the rest-frame UV light, yielding little information on the underlying mass distribution. Taking advantage of our recently completed NICMOS-GOODS 180-orbits survey, as well as the sensitivity and superior PSF (Fig. 1d) of the future WFPC3 and JWST NIR camera, we will probe the rest-frame optical/NIR light out to $z > 4.0$, less than 2 Gyr after the Big Bang. This will enable us to probe the structure and mass of galaxy components at early epochs when the first disk galaxies are assembling, and the quasar luminosity function peaks.

Studies to date have primarily focused on the evolution of massive luminous ($L > L^*$) galaxies. The fainter galaxy population (which experiences a larger fractional growth at later epochs) has proved harder to map out, in large part due to the difficulty of acquiring accurate spectroscopic redshifts for large samples of sources fainter than R(Vega) $\sim$ 24-25. In order to expand these studies into new regimes, I plan to use the GMT multi-object spectrograph, which should reach R(Vega) $\sim$ 26 in several hour exposures. The GMT will also allow optical/near-IR imaging and spectroscopy of the fainter and more distant star-forming galaxies: this will complement our WFPC3 and JWST studies by constraining the dynamics and kinematics of the assembling galaxies. It is interesting to note that challenges to hierarchical models are already emerging from recent studies (Genzel et al. 2008; Bournaud et al. 2008; WJKBK08), which suggest that major mergers, may not be responsible for the stellar buildup observed in massive galaxies.

One critical missing ingredient needed to piece together galaxy evolution is a census of the cold gas in galaxies at intermediate and high redshifts. I plan to use ALMA and CCAT to trace cold gas and dust in such systems and thereby constrain the physical properties of their ISM, their star formation history, and dynamical masses. Such observations can yield insights into the nature of the large population of dusty submillimeter galaxies, the decline in cosmic SFR density (e.g., Jogee et al. 2008a,b), and the starburst–AGN connection. In 12 hours, ALMA reaches a 1 σ continuum r.m.s. of 7, 20, 30, 200 μJy respectively at 3mm, 1.3mm, 870μ, and 440μ. Due to the negative K-correction in the mm/sub-mm (300–2100 μ) regime, ALMA will easily detect star forming galaxies out to $z \sim 10$. With its high resolution and small field of view, ALMA will be ideal for targeted surveys, but unsuitable for large-area surveys. CCAT will complement ALMA by providing a mapping speed, which exceeds that of ALMA by factors ranging from 1760 to 12 in the wavelength range 350–3000 μm.

I expect that these future explorations will provide a stringent test-bed for hierarchical models of galaxy evolution. They will advance our understanding of how the fundamental building blocks along the Hubble sequence assembled over the last 12 billion years.

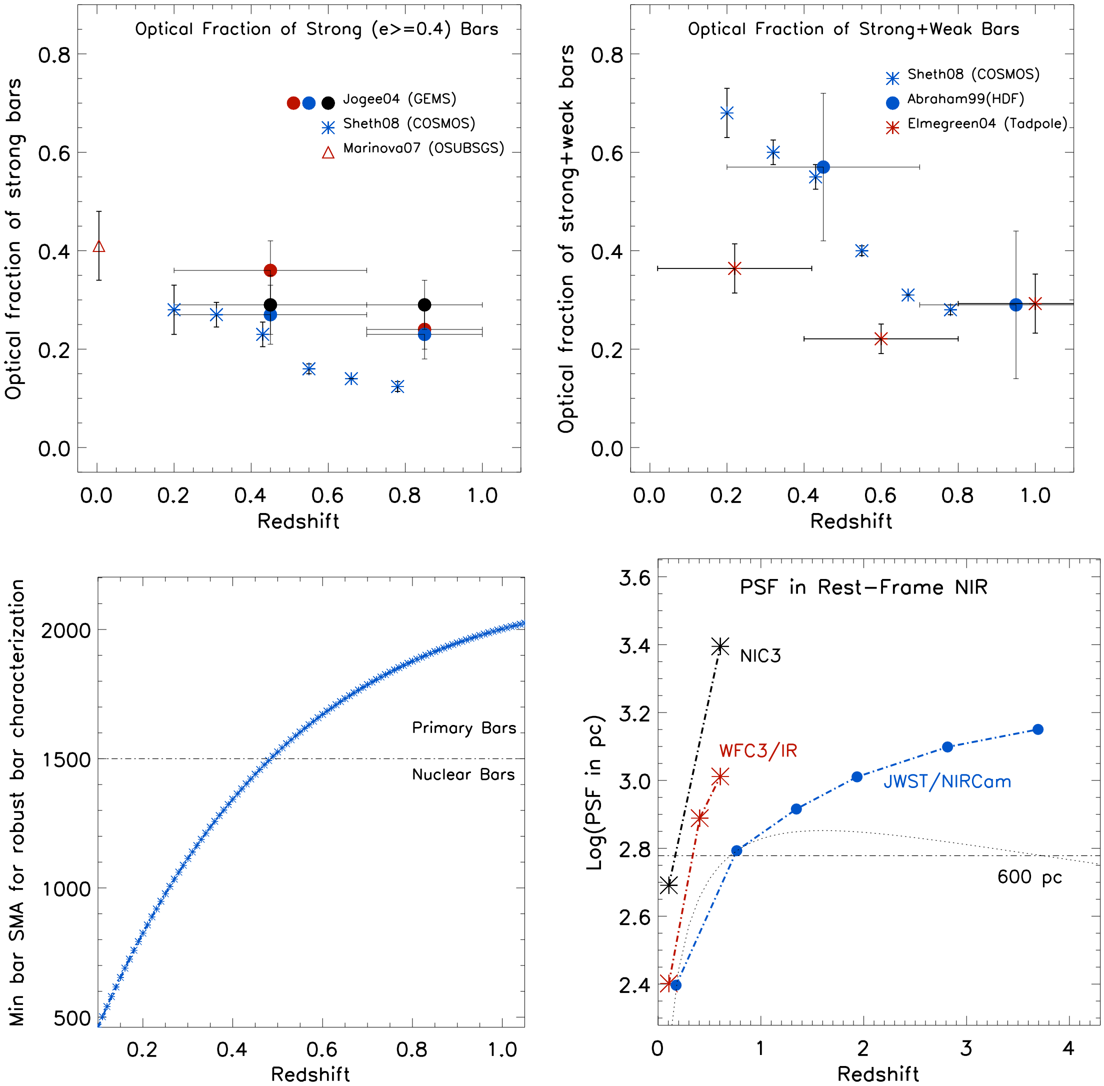


Fig. 1a (Top Left): The observed rest-frame optical fraction of *strong (ellipticity* $e \geq 0.4$*)* bars as a function of redshift is shown for the studies by Jogee et al. (2004), Marinova & Jogee (2007), and Sheth et al. (2008). The red, black, and blue filled circles show the results obtained using three commonly used techniques (based on Sérsic cuts, rest-frame color cuts, and concentration indices) to identify spiral galaxies. See § A2 for details. **Fig. 1b (Top Right):** As in 1a, but showing the observed rest-frame optical fraction of *(strong+weak)* bars. **Fig. 1c (Lower Left):** We show the minimum semi-major axis ($a_{\rm min}$) that a bar must have so that it can be robustly characterized using ellipse-fitting and the quantitative criteria in Jogee et al. (2004). We increasingly lose primary bars with a in the range of 1.5 to 2.0 kpc at $z > 0.5$. **Fig. 1d (Lower Right):** Future observations in the rest-frame NIR with WFC3 and JWST will enable us to trace optically-obscured primary bars of intermediate sizes, at the resolution (PSF) shown.

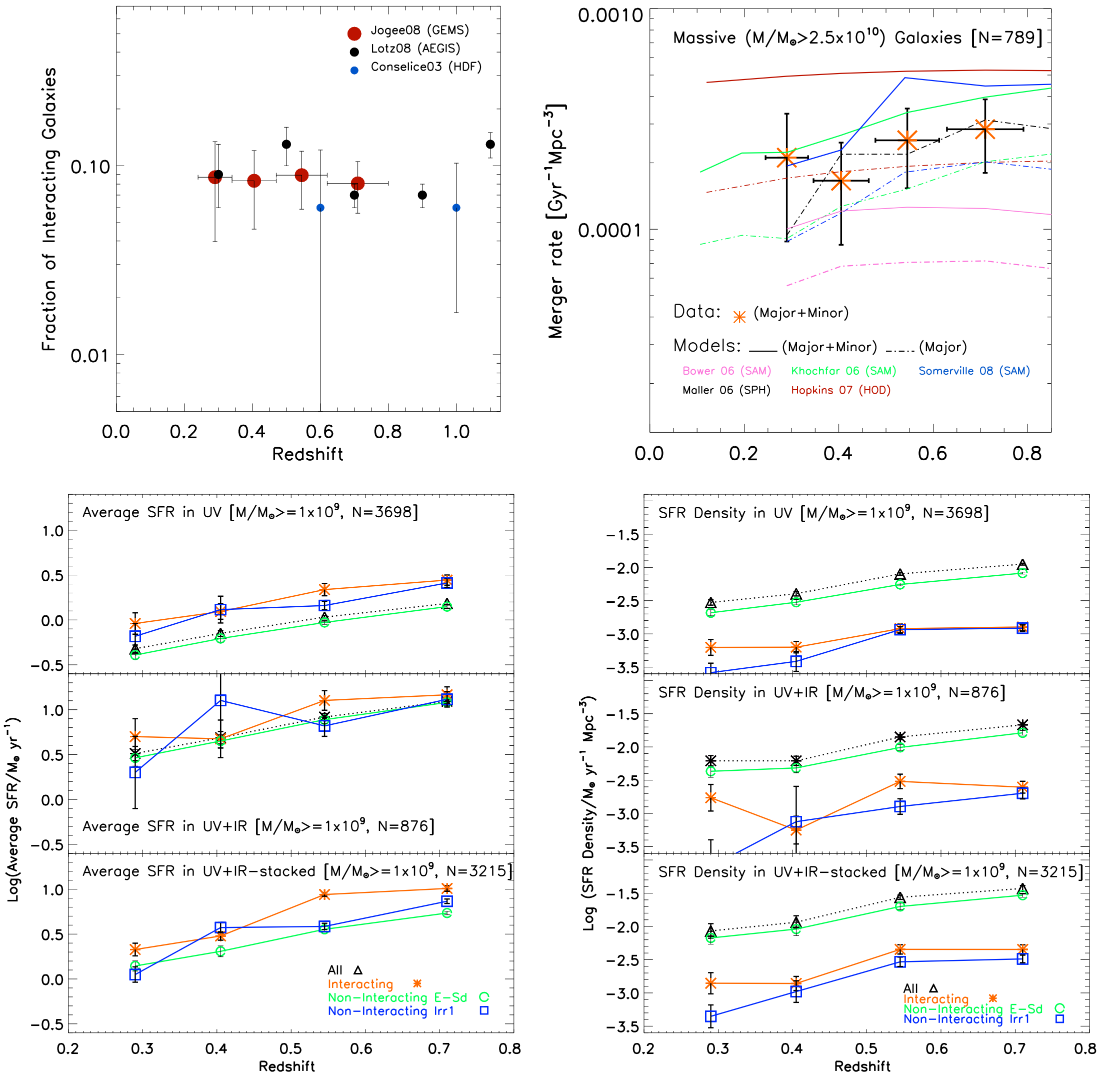
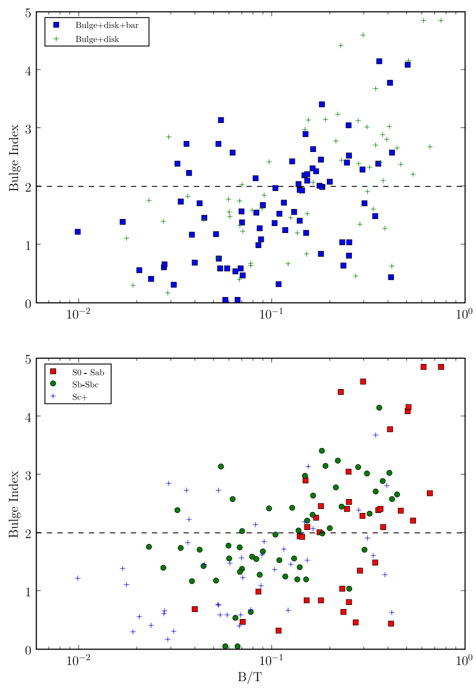


Fig. 2a (Top Left): We show the observed fraction of interacting/merging galaxies from Lotz et al. (2008), Jogee et al. (2008b), and Conselice (2003). **Fig. 2b (Top Right):** The empirical rate of galaxy mergers with mass ratio $M1/M2 > 1/10$ (orange stars) among high mass galaxies is compared to the rate of (major+minor) mergers (solid lines) predicted by different ΛCDM-based models of galaxy evolution. **Fig. 2c (Lower Left):** The average SFR of interacting and non-interacting galaxies are compared. The average UV-based SFR (top panel; based on 3698 galaxies), average UV+IR-based SFR (middle panel; based on only the 876 galaxies with 24um detections), and average UV+IR-stacked SFR (based on 3215 galaxies with 24um coverage) are shown. In all there cases, the average SFR of interacting galaxies is only modestly enhanced compared to non-interacting E-Sd galaxies over $z \sim 0.24$–0.80 (lookback time $\sim$ 3–7 Gyr). **Fig. 2d (Lower Right):** As in. 2c, but now showing the SFR density of galaxies. In all bins, interacting galaxies only contribute a small fraction (typically below 30%) of the total SFR density. [All figures are from Jogee et al (2008b)]



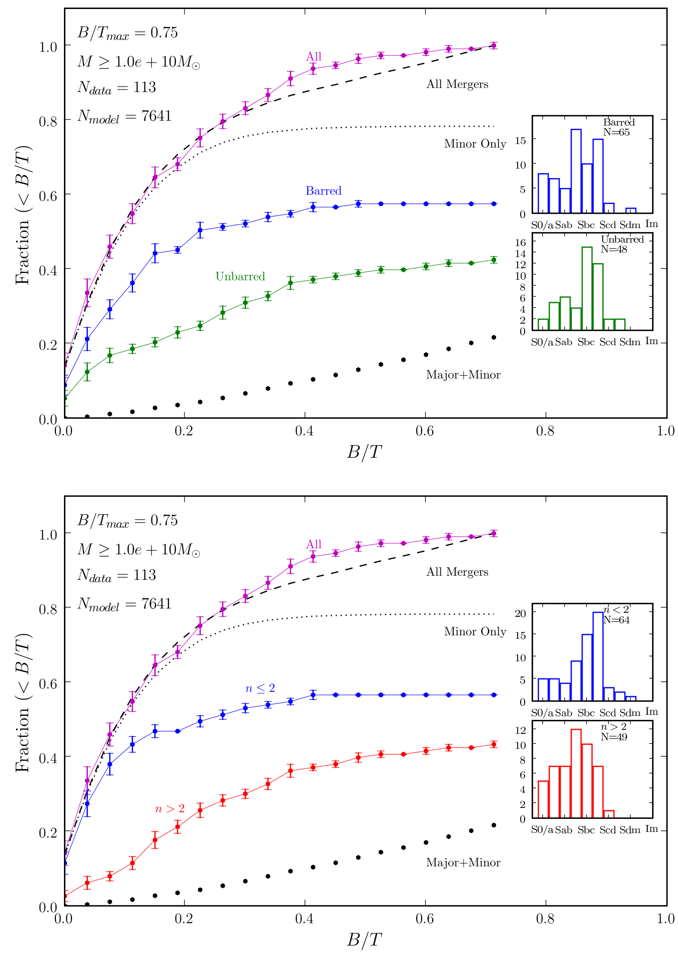


Fig. 3a (Left): The relation between B/T and bulge index is shown. The legend indicates the type of decomposition used for each data point. Note that as many as 60% of bright spirals have low $n \leq 2$ bulges: such bulges exist in barred and unbarred galaxies across all Hubble types, and their B/T ranges from 0.01 to 0.4, with most having $B/T \leq 0.2$. **Fig. 3b (Right):** For high mass ($M_{\star} \geq 1.0 \times 10^{10} M_{\odot}$) spirals, we compare the empirical distribution of bulge-to-total mass ratio (B/T) to predictions from ΛCDM-based simulations of galaxy evolution. The y-axis shows the *cumulative* fraction F of galaxies with $B/T \leq$ a given value. The magenta line shows F from the data, while the other two colored lines break this F in terms of bar class (top panel) or bulge n (lower panel) The black dashed line shows F from all model galaxies, while the black dotted line and black dots show the contribution of model galaxies that experienced, respectively, *only past minor mergers* and *both major and minor mergers*. In the models, the fraction ($\sim 3\%$) of high mass spirals, which have undergone a past major merger and host a bulge with $B/T \leq 0.2$ is *a factor of over 15 smaller* than the observed fraction ($\sim 66\%$) of high mass spirals with $B/T \leq 0.2$. Thus, *bulges built via major mergers seriously fail to account for most of the low $B/T \leq 0.2$ bulges present in $\sim 66\%$ high mass spirals.* [All figures are from Weinzirl, Jogee, Khochfar, Burkert, & Kormendy (2008)]

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