CURRENT RESEARCH (Shardha Jogee)

Recent developments in astrophysics have revolutionized our understanding of the Universe. Basic predictions of the standard model of particle physics (e.g., the Higgs boson; CMS collaboration et al. 2012) and of the inflationary Big Bang theory have been confirmed, and strong constraints on the age and geometry of the Universe (e.g., Komatsu et al. 2011; Planck Collaboration et al. 2013) are in place. Observations leading to the 2011 Nobel prize in Physics have conclusively established that the Universe is accelerating at an expanding rate, powered by an enigmatic component called dark energy, which accounts for a whopping $\sim 72\%$ of the total energy density in the Universe. Non-baryonic dark matter[1] make up another $\sim 24\%$, while ordinary matter made of baryons constitutes but a mere $\sim 4\%$.

Yet, while much progress has been made on cosmological scales, fundamental questions remain. What is the cause of inflation? What is the nature of dark matter and dark energy? How did the Universe evolve from a nearly uniform cosmic soup into stars and planets? How did baryons, central black holes, and dark matter assemble over time into galaxies – the core building blocks of the Universe?

My research tackles cardinal questions on the evolution of galaxies. How do galaxies grow their stars, black holes, and dark matter halos across cosmic times and vastly different environments? What is the role played by theoretically-predicted growth modes, such as violent mergers of galaxies (e.g., Cole 2000; Hopkins et al. 2010a), and more 'quiescent' modes, such as gas accretion along cosmological filaments (e.g., Kereš et al. 2005; Dekel et al. 2009), and secular evolution (e.g., Kormendy & Kennicutt 2004)? How does the star formation and black hole activity in the Universe evolve? How do galaxy clusters – some of the largest bound structures in the Universe – form?

My research group addresses these questions using some of the largest and deepest galaxy surveys to date (§ A1 and § A4). We also work with recognized theorists (e.g., Drs. Khochfar, Burkert, Hopkins, Hernquist, and Somerville) to compare our empirical results with theoretical models in order to improve the model baryonic physics and advance galaxy evolution paradigms (§ A2 and § A3). Over the last nine years, I have received federal science and education grants totaling \$2,341,049. Science grants account for \$1,640,049, of which \$1,018,748 are from grants where I am the Principal Investigator (PI). My current publication record includes 156 papers, 4879 citations, and has an h-index of 37. Below are excerpts of my research program focusing on questions led by myself or my past students and postdocs (e.g., Tim Weinzirl, Irina Marinova, Amanda Heiderman, Kyle Kaplan, Fabio Barazza, Ingo Berentzen, Sarah Miller, Kyle Penner, etc)

(A1) Role in International Science Collaborations: I am a Co-Investigator on five international science collaborations, which have conducted some of the largest and deepest survey of galaxies (e.g., GEMS (Rix et al. 2004), GOODS (Giavalisco et al. 2004), STAGES (Gray et al. 2009), the Hubble ACS Treasury survey of Coma (Carter et al. 2008), and the GOODS-NICMOS Survey (Conselice et al. 2011)) with NASA's *Hubble Space Telescope*. Since the role of members within large collaborations is often unclear, I would like to clarify that my research group and I are *leading* many of the core papers on the structure, merger, and assembly history of galaxies in the above five science collaborations (e.g., Jogee et al. 2004, 2009; Marinova, Jogee, et al. 2007, 2009, 2012;

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[1] Dark matter emits no electromagnetic radiation and is detected through gravitational effects.

Heiderman, Jogee, et al. 2009; Weinzirl, Jogee, et al. 2009, 2011, 2013; Barazza et al. 2006, 2008, 2009a, 2009b, etc)

(A2) The Merger History of Galaxies: In Jogee et al. (2009), we explored the rate of galaxy mergers and their impact on the cosmic star formation activity. The strengths of our study included the analysis of a very large sample of high-mass galaxies galaxies and a demonstration of the robustness of the results through the use of two independent techniques to identify galaxy mergers, and the use of three different methods to quantify the star formation rate. Contrary to common lore, we found that over half of the age of the Universe, only at most 30% of the cosmic star formation rate density can be assigned to visibly interacting galaxies. Instead, the bulk of new stars are being churned out in relatively isolated benign systems. Our results have been confirmed since by several other studies (e.g., Robaina et al. 2010; Lotz et al. 2011; Hopkins et al. 2010b). We also set the first empirical constraints on the rate of minor mergers of galaxies, showing that minor mergers are at least three times more frequent than major mergers.

We also compared our empirically-derived merger rate to theoretical predictions by different models (halo occupation distribution models, semi-analytic models, and hydrodynamic simulations) from different theorists (e.g., Hopkins, Khochfar, Somerville, Benson, Bower, Maller). These overdue comparisons revealed that while all models predicted a shallow slope for the evolution of the merger rate with time, there was a surprisingly large dispersion in the *absolute value* of the merger rate predicted by different models (e.g., see Figure 12 in Jogee et al. 2009). This result spawned active brainstorming among the afore-mentioned theorists, leading them to publish a subsequent paper that revisited theoretical models and re-assessed their uncertainties (Hopkins et al. 2010c).

(A3) Probing Galaxy Assembly History via 'Structural Archaeology': 'Structural Archaeology' – the census of distinct stellar structures at different epochs – unveils the assembly of galaxies and allows us to assess the importance of different modes of galaxy growth (e.g., violent stellar processes associated with galaxy mergers; gas accretion from halo and cold streams). In the last decade, my group has been exploring how and when classical bulges, stellar disks[2], and bars – the core stellar components of present-day galaxies along the seminal Hubble sequence – assembled over the last ten billion years (e.g., Jogee et al. 2004, 2005, 2009; Marinova, Jogee et al. 2007, 2009, 2012; Weinzirl, Jogee et al. 2009, 2011, 2013; Barazza et al. 2008, 2009a, 2009b, etc).

Some of our early work focused on stellar bars – the most efficient internal driver of gas inflows in disk galaxies. Jogee et al. (2004) uncovered that strong bars were common in massive disk galaxies over the last eight billion years – a time interval[3] long enough for bars to drive significant secular evolution of galaxies. In Jogee et al. (2005), we explored molecular gas and star formation in the central regions of barred galaxies, showing that the large difference in star formation 'efficiency' is likely tied to different stages of bar-driven inflow, and to the density of the gas with respect to a critical density for star formation. From several of our studies (Marinova et al. 2009, 2011; Marinova & Jogee 2007; Barazza et al. 2009a, 2009b; Maltby et al. 2012), we are finding that the bar fraction in galactic disks does not show large variations with environment, a result with implications for competing physical processes that induce and weaken bars in clusters.

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[2] We use the term 'disks' to denote the large-scale outer disks of galaxies, as well as central disks and pseudo-bulges (e.g., Kormendy 1993)

[3] A time interval of eight billion years corresponds to approximately 60% of the age of the Universe

In Weinzirl, Jogee, et al. (2009), we found that most massive *field* spiral galaxies harbor pseudo-bulges (with very low bulge-to-total mass ratio and disky characteristics) rather than classical bulges. These results actually show good agreement with theoretical predictions by Khochfar and Silk (2006), and Hopkins et al. (2009) – an agreement essentially driven by the fact that in the models less than 20% of *field* spirals undergo a major merger over the last ten billion years. The remaining spirals grow by minor mergers, gas accretion, and secular processes. While this work reduces the tension between theory and observations for field galaxies, one should note that hydrodynamical models still face challenges in producing purely bulgeless massive galaxies in different environments.

In a follow-up work, we extend our analysis to the central part of the Coma cluster – one of the richest and densest local environments – where we find that most ($\sim$ 57%) of the stellar mass in galaxies appears to dynamically hot classical bulges/ellipticals (Weinzirl, Jogee, & the Hubble Treasury Survey of Coma Collaboration 2013, submitted). Theoretical models, lacking in cluster physical processes, fail miserably to match the global properties of the Coma cluster, strongly over-predict the ratio of cold gas mass to stellar mass, and under-predict the mean fraction of stellar mass locked in dynamically hot components.

Extending our exploration to early epochs, we find that when the Universe was a fifth of its present age, the majority of massive galaxies were disk-dominated and over a third were ultra-compact – a radically different situation from present-day massive galaxies (Weinzirl, Jogee, & the GOODS NICMOS Survey Collaboration 2011). Most X-ray identified active black holes also reside in extended disky galaxies. These results have important ramifications as current state-of-the theoretical models (Ceverino et al. 2010; Oser et al. 2012) severely fail to produce this large fraction of extended disk galaxies (Jogee et al. 2013, in prep.; Ceverino et al. 2013, in prep.), despite the fact that these models already include gas-rich major mergers (Hopkins et al. 2009) and cold streams that help to form disks.

(A4) The VIRUS-P Exploration of Nearby Galaxies (VENGA): VENGA is the largest integral field spectroscopic survey of nearby spiral galaxies conducted to date. It uses 150 nights of observing time with the superb VIRUS-P Integral Field Unit (IFU) on the 2.7m telescope at McDonald Observatory. VENGA was a team effort spear-headed by graduate student PI Guillermo Blanc, but was only 40% complete at the time Blanc graduated. Other graduate students in my group took over and our observing proposals were allocated $\sim$ 90 more nights to complete the survey. I am the PI of an NHARP grant entitled 'Student Support for VENGA: Understanding Galaxy Evolution in the Nearby Universe', which has supported graduate students for conducting observations, developing the data reduction pipeline; and performing scientific analyses. VENGA is now 99% complete (Blanc et al. 2013a) and provides a phenomenal database of $\sim 44,000$ independent exquisite, spatially-resolved, moderate resolution blue and red spectra out to large radii. It is spawning a wide range of scientific investigations on star formation (Blanc et al. 2013b), chemical evolution of spirals (Kaplan, Jogee, Kewley et al. 2013, in prep.), AGN (Hao, Jogee, et al. in prep.), stellar populations and star formation history (Song, Gebhardt, et al. in prep.; Weinzirl, Jogee, et al. in prep).

FUTURE DIRECTIONS

(A5) The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX): HETDEX (PI: G. Hill) is a UT-led international spectroscopic survey starting in 2014 at McDonald Observatory. In addition to constraining the nature of dark energy, HETDEX will allow an unprecedented study of galaxies. I am the UT PI of a proposal submitted to NSF for exploring galaxy evolution as a function of environment in a 28 $\deg^2$ subfield called the HETDEX/SHELA field. We will probe galaxies along the cosmic web over a phenomenal 0.5 Gpc^3 comoving volume[4] that hosts several hundreds of massive proto-clusters. We will target the exciting epoch when the Universe was less than 15% of its present age, the cosmic star formation and black hole activity reached a maximum, and proto-clusters started to gravitationally collapse into existence.

(A6) Next-Generation Facilities (GMT, CCAT, JWST): The frontier questions we need to address over the next decades require sophisticated multi-wavelength facilities that are phenomenally expensive to construct. There will be only a handful of such facilities worldwide. Public facilities, such as the James Webb Space Telescope (JWST[5]), will be accessible to the general community, but only partner institutions will have access to privately-funded facilities, such as the Giant Magellan Telescope (GMT[6]) and the Cerro Chajnantor Atacama Telescope (CCAT[7]). This preferential access will place these partner institutions in a prime position to lead scientific breakthroughs, recruit the best faculty and students, and leverage funding opportunities. The UT Astronomy Department is gearing up for such a leadership role through its planned partnership in the GMT and proposed partnership in the highly complementary CCAT.

My research program will hugely benefit from the synergy between JWST, GMT, and CCAT. We will use the high resolution infrared images from GMT and JWST to extend our exploration of galaxy evolution (§ A2, A3, A4) out to epochs when galaxies were in their infancy. For instance, in an unprecedented step, the GMT near-infrared camera will enable us to resolve young galaxies in advanced merger stages, where their double nuclei are separated by only a few hundred parsecs, akin to the archetypical nearby Arp 220 merger. It will also allow us, for the first time, to dissect the enigmatic ultra-compact massive galaxies present ten billion years ago (§ A3).

CCAT complements the infrared capabilities of GMT and JSWT by operating in the radio and submillimeter bands where half of the light in the Universe is emitted. We will use CCAT to nail the cosmic history of star formation and black hole activity out to the formative stages of the young Universe. CCAT can provide a critical missing ingredient for HETDEX by mapping the obscured star formation rate down to several solar masses per year at early epochs. I estimate that we can map half of the HETDEX/SHELA field down to this depth in 100 nights – a large but achievable time allocation as a partner. The powerful CCAT-GMT synergy will enable us to map star-forming galaxies in different evolutionary phases and secure spectra of the fainter more distant systems.

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[4] Over the redshift interval $1.9 < z < 3.5$, a sky coverage of 28 $\deg^2$ corresponds to a comoving volume of 0.5 Gpc^3, where 1 Gpc refers to 10^{25} m.

[5] JWST is an infrared space telescope set to launch in 2018. It is funded by NASA, the European Space Agency, and the Canadian Space Agency.

[6] GMT is a privately-funded 25-meter optical/infrared telescope scheduled for 2020 with an estimated cost of 700 million USD.

[7] CCAT is a privately-funded 25-meter submillimeter telescope scheduled for 2019, with an estimated cost of 140 million USD.

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