Session V

Lessons from Large Surveys

https://doi.org/10.1017/S1743921310002772 Published online by Cambridge University Press

Stellar Populations - Planning for the Next Decade
Proceedings IAU Symposium No. 262, 2009
Gustavo Bruzual & Stéphane Charlot, eds.

doi:10.1017/S1743921310002772

What have we learned from large spectroscopic surveys?

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Abstract. An essential use of stellar population synthesis methods is to interpret the observations of galaxies, to infer their star-formation and assembly histories. I describe here some of the uses of these techniques over the past few years, primarily in the context of local galaxy redshift surveys. For this purpose, such surveys have both advantages and disadvantages relative to higher signal-to-noise but smaller studies, which I discuss. After discussing general issues, I describe how the substantial model uncertainties impact the analysis of galaxy spectra. Then, I discuss the special case of elliptical galaxies, arguing that investigators have made interesting discoveries even in the absence of perfect (or even good) models. I then describe the desiderata for massive higher redshift surveys and the trade-offs that must be made between cosmological and galaxy-focused science, in qualitative terms.

Keywords. galaxies: statistics, galaxies: stellar content, galaxies: fundamental parameters

1. Overview

To understand the formation and growth of galaxies, a crucial element is understanding how stars evolve (Tinsley 1980). The ultimate sources of luminosity in a galaxy are the nuclear reactions occurring inside of stars. Interpreting the resulting spectrum of light emitted by the galaxy requires understanding how the light is emitted from the stellar photospheres and how the stars themselves evolve over time, including the dependence on metallicity and stellar abundance ratios.

In this review I will discuss recent work on using what we know about stellar evolution to better understand the nature of galaxy growth and star-formation over cosmic time. Current stellar population synthesis models offer a tantalizing glimpse of the constraints that such techniques could put on galaxy formation models. Certainly even now we can see that at least some parameters in these models — stellar mass, most notably — have a certain validity. Furthermore, galaxy spectra show such regularity, even with respect to the range of *possible* formation histories, that most astronomers are convinced that they can successfully constrain theoretical parameters. However, significant uncertainities remain, on the overall stellar mass scale and the determination of metallicities and abundances.

My focus here is less on the stellar population modeling techniques themselves, and instead on how they have been used to fit galaxy populations. In some cases the modeling uncertainties simply preclude any solid conclusion — however, I will try to highlight conclusions that appear robust to these uncertainties.

2. What do we want to know?

Any "grand plan" for better understanding galaxies and how they have grown must involve determining:

(a) the amount of gas mass processed into stars over time
(b) the star-formation rates of galaxies
(c) the gas-phase and stellar-phase metallicities
Understanding the stellar populations is directly related to making these determinations.

However, as we shall see, current stellar population models have large uncertainties that cannot be resolved in the near future: the exact form of the stellar initial mass function (IMF), the nature and history of post-main sequence populations, the impact of mass loss on horizontal branch stars, and the incidence of blue straggler and binary stars. The experts on stellar populations in this symposium have highlighted these uncertainties in great detail.

Put most simply, the existence of these uncertainties mean that we cannot determine the stellar masses of galaxies (because of the IMF), the precise star-formation rates (because of the contamination due to old but hot stars), or the metallicities and abundances (for a variety of reasons). These facts need not cause us to lose heart entirely — but we do need to (a) redefine our goals and (b) try to use multiple independent constraints to check our results for consistency.

Thus, we can reduce our expectations and still answer interesting questions about the growth of galaxies. For example, while the absolute mass of stars that are formed with time cannot be determined, for "similar" galaxies we might expect that the unknown IMF is at least *similar* within that group. In fact, as we will see, it appears likely that there is not a tremendous range of IMFs within, say, the class of ellipticals or the class of spirals. Similarly, while the absolute calibrations of gas-phase metallicity indicators are a matter of debate, most models agree up to a normalization constant.

For these reasons, if we restrict analyses to *relative* comparisons among galaxy subclasses, environments and redshifts, we can make interesting statements relative to theoretical predictions. This approach is well-justified, especially given the inherent uncertainties in the galaxy formation models to which we will compare these results.

3. Pros and cons of large spectroscopic surveys

There is a huge amount we have learned about these topics from small, high signal-to-noise ratio, carefully analyzed samples. Elsewhere in this symposium, Martin Bureau makes an eloquent case for the necessity of such samples, such as SAURON (Bacon *et al.* 2001). What I discuss here is a *different* approach, which is to use the most massive spectroscopic surveys, such as the Sloan Digital Sky Survey (SDSS; York *et al.* 2000). such surveys will inevitably be lower signal-to-noise and have systematic issues that more concentrated efforts can avoid.

What are the main advantages of a massive survey? They primarily flow from the sheer size of the available sample:

(a) **Environmental breadth**: They include objects in all environments, including clusters, groups, and void regions. This advantage particularly allows us to understand the isolated systems (which may well be the simplest) using a large sample; they are difficult even to *find* without a large survey.

(b) **Objective selection**: Investigators often try to achieve breadth in mass range, environment, and galaxy type in a small sample through hand-picked selection (cf. SAURON, SINGS, THINGS, etc.). In most cases, this process yields a subjective sample, with unknown systematics due to that selection. While this can be avoided, the smallness of the sample makes such selection an almost irresistable temptation. Such samples are still incredibly interesting, but having objective samples can put them more properly into a broader context.

https://doi.org/10.1017/S1743921310002772 Published online by Cambridge University Press

(*c*) **Homogeneity of data and data analysis**: With very large surveys, one is forced into a "factory" mode of data analysis — the data is homogeneously analyzed by necessity. In addition, with huge datasets some calibration issues (such as photometric calibration) are completely solved problems (e.g., Padmanabhan *et al.* 2008). More and more commonly, smaller samples are also analyzed by mostly automated pipelines, but they very rarely have had the amount of work and cross-checks that larger surveys with more participants do.

(*d*) **Pure statistical power**: With great numbers comes greater statistical power: the ability to find very unusual objects (Fan *et al.* 2001), detect weak correlations, or to disentangle competing effects (e.g., Kauffmann *et al.* 2003, Blanton *et al.* 2003a).

The main disadvantages of massive surveys typically are the flip side of the advantages — and have already sprung to the minds of critical readers:

(*a*) **Lower signal-to-noise and/or resolution**: Almost by definition, one has created a massive survey by cutting corners in signal-to-noise ratio or resolution or both. Thus, the precision per galaxy is surely lower — this effect can make it near impossible to (say) disentange age and metallicity on a galaxy-by-galaxy basis.

(*b*) **Catastrophic failures**: With small samples, catastrophic pipeline failures can be identified and fixed in all cases: for massive surveys, not all problems can be followed up, because there are too many of them! That is, homogeneous data analysis does not always produce homogeneous quality! Among other things, this effect makes it harder to find truly weird objects in the presence of the failure-induced outliers.

(*c*) **Not always tuned to your problem**: Another way one creates a massive survey is to pool the resources of many scientists, which always introduces compromises in design. That is, if you and your small group decide to proceed with a small focused survey, you can design it to achieve precisely your goals. If you are collaborating with many other scientists to do something massive, the survey will be excellent primarily in the areas where everyone's interest overlaps (or — equivalently? — in areas necessary for cosmological parameter estimation). An example is that the SDSS has fibers only 3 arcsec in diameter, excellent for maximizing signal-to-noise for redshift determination, but potentially misleading for galaxies with substantial chemical gradients (e.g. Vila-Costas & Edmunds 1992, Zaritsky *et al.* 1994).

4. The impact of model uncertainties

Ignoring for the moment the issue of the fiber aperture, let us consider the case of the SDSS. This survey yields moderate resolution ($R \sim 2000$), moderate signal-to-noise ($S/N \sim 4$ per pixel) optical spectra of galaxies at around $z \sim 0.1$, spectrophotometrically calibrated. How well can one use such spectra to constrain galaxy histories?

Purely statistically speaking, these spectra have tremendous power. Consider, as just one example, the work of Tojeiro *et al.* (2009) and the rest of the VESPA team. They publish detailed fits to the star-formation histories of SDSS galaxies. In a clever fashion, by iteratively applying non-negative (but otherwise linear) fits in successively denser model grids, they design their algorithm to adaptively smooth the result such that they avoid degeneracies in their results. As an aside, we note that their approach does not yield *independent*, or even *uncorrelated* errors between bins. Also, their approach to model selection is very likely more aggressive in terms of using parameters than alternatives such as cross-validation or the Bayesian Information Criterion.

Even with these caveats, the statistical power is impressive. For example, seemingly innocuous-looking Sa galaxies appear from this spectral analysis to have interesting histories of star-bursts. The metallicities, and indeed metallicity histories, are strongly

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constrained. These authors have taken the interpretation even further, for example, publishing the cosmic star-formation history out to redshift $z \sim 4$ inferred from the local galaxy population, and, even more ambitiously, publishing maps of the metallicity history as a function of location in the local Universe (Panter *et al.* 2008). These results provide some support for the "downsizing" picture, yielding nearly flat star-formation histories for low mass galaxies, but star-formation histories for high mass galaxies that rise into the past. Clearly there is truth to these conclusions: after all, the most massive systems *are* dead and red, and the faint end of the galaxy sequence is dominated by blue galaxies, whose star-formation histories are consistent with flat.

However, all of these results are highly dependent on the underlying stellar populations modelling — as of course the authors of such studies understand very well! The most thorough current effort at evaluating the impact of such uncertainties seems to be the ongoing work of Conroy *et al.* (2009). Others are hard at work improving the models (e.g. Bruzual 2007, Schiavon 2007, Maraston 2005), but Conroy *et al.* (2009) seem to be the only ones trying to marginalize over the full uncertainties. They have evaluated (for example), the dependence of mass-to-light ratios on assumptions about TP-AGB stars, the horizontal branch populations, and the IMF. These each introduce large (0.1 dex-ish) uncertainties.

A characteristic problem resulting from such model-related issues is seen in the analysis of Luminous Red Galaxies by Tojeiro *et al.* (2009). They show what is ostensibly the mean star-formation history of such galaxies (from spectra spread from $0.01 < z < 0.25$) averaged over the past 10 billion years. The star-formation rate declines from an early peak, then shows a factor of 30 rise over the last 100 million years. Only an especially perverse configuration of galaxies across redshift could produce such a *mean* behavior if the galaxy selection is uniform and the models are correct! Lest I appear overly critical to these authors, I will note the same upturn is seen in the mean LRG star-formation history found by Blanton & Roweis (2007). It almost certainly results from an incorrect accounting for hot stars of some sort in the old stellar population (there may be young stars in LRGs *too*, but they cannot have the inferred age distribution).

In more detail, some major sources of uncertainty are as follows:

(*a*) **Initial mass function**: The IMF impinges directly on all calculations, because some observations (say of Hα emission or other signs of recent star-formation) are dominated by the most massive stars, while others (say the optical continuum of oldish stellar populations) are dominated by 1–2 $M_\odot$ stars. Thus, comparing star-formation rates to stellar masses requires an assumption of the IMF. In addition, stellar masses are generally defined to extend to the hydrogen-burning limit at 0.08 $M_\odot$, meaning a substantial fraction of the quoted stellar mass is in objects which contribute essentially zero signal to the observations. (One might ask why the brown dwarfs and free planets are excluded, though at least these populations are thought to comprise only a small fraction of the total mass). The IMF uncertainty induces a shift in mass-to-light ratio in K of up to 50% (see Baldry *et al.* 2008). Extreme IMF changes can even change the color evolution of a galaxy up to 0.1 mag in $V - K$ (Conroy *et al.* 2009).

(*b*) **TP-AGB stars**: Asymptotic Giant Branch stars undergo double shell burning: an outer hydrogen shell and an inner helium shell. Such configurations are unstable to thermal pulsations, which cause them to vary in temperature and luminosity in a manner that is difficult to predict. Furthermore, this phase is extremely short-lived, and thus observations of it are rare. The interesting feature of this source of uncertainty is that its effects are largest in the near-infrared — V-band mass-to-light ratios are hardly changed but Conroy *et al.* (2009) claim that reasonable changes in the assumed temperatures or luminosities of TP-AGB stars can change $V - K$ by up to 0.5 mag!

(*c*) **Horizontal branch stars**: The impact of the horizontal branch phase of stellar evolution on the resulting spectrum is determined by how much mass loss occurred during the preceding red giant branch phase. HB stars are luminous, but can be either very hot and blue, or quite red, depending on whether very much or very little mass loss occurred. HB color correlates with metallicity — redder clusters are more metal-rich — but with exceptions (Rich *et al.* 1997). The HB stars are likely important for understanding the UV-upturn effects in elliptical galaxies, and can be confused with star-formation (Schawinski *et al.* 2007; see also Martin Bureau's contribution to this symposium).

With these caveats in mind, we have to be careful to distinguish *physical* parameters of the galaxies that we know to a few percent, such as spectral energy distributions and luminosities, from *theoretical* parameters of the galaxies whose calibrations are still highly uncertain, such as stellar mass and star-formation rate. However, as we will describe below, there is reason to be somewhat more hopeful — after all, in the face of all these *possible* variations, galaxy populations are known to be quite *regular*.

5. Index measurements vs. full SED fits

In the example above, the VESPA code fit a model to the entire SED of each galaxy, an approach also taken by others, e.g. Conroy *et al.* (2009). An important and more commonly used alternative to that approach is to instead use *index* measurements: simple manipulations of the spectrum, often local in wavelength, intended to capture important effects. There are trade-offs in choosing one approach over another.

The index approach is epitomized by the Lick index system (see Trager *et al.* 2000 and Schiavon 2007 for modern discussions of this system). Essentially, most of the indices measure the fractional absorbtion of a given line or combination of lines, using the surrounding regions of the spectrum to estimate the continuum being absorbed. Since in cool stars there are myriad lines in the spectrum, the interpretation can be complicated (and indeed the indices greatly affected) by absorption lines in the continuum bands. An exception to this model is the D4000 index, which measures the break at 4000Å, a tracer of the stellar population age (Balogh *et al.* 1998).

Index methods have an advantage over full spectral fits, in that they often are less sensitive to absolute spectrophotometric calibrations, and similarly less sensitive to dust absorption (to the extent that it acts as a screen, of course — complex dust morphologies can cause index changes). However, they throw away a considerable amount of information in the spectrum.

An interesting approach is that of the MOPED algorithm (Reichardt *et al.* 2001), which uses SED models to identify the most "interesting" directions in spectrum space, reducing the fitting routines to fitting those components, instead of a more general model. Of course, because their approach is based on principal components analysis, it does not result in "local" measurements of the spectra. It would be interesting to derive a similar approach, to find the most informative parametrizations of a spectrum *in the presence of calibration uncertainties.* A more ambitious investigator might ask the same questions but also in the presence of *model* uncertainties!

Gallazzi *et al.* (2006) present results for galaxy observations from the SDSS using index fits to the Balmer lines, D4000, and metal absorption lines. As do Panter *et al.* (2008), they present the inferred star-formation histories and metallicity content of galaxies. It is comforting that these two efforts find similar results despite their quite different approaches to fitting the models.

6. Can we use uncertain theoretical parameters?

I argue quite forcefully: yes. Above, I commented on the well-known problems in interpreting stellar population models — I do not believe we can accurately derive stellar masses, or metallicity histories, or galaxy-by-galaxy star-formation histories. And yet it would be foolish to think that the uncertainties hamstrung us completely.

After all, galaxies are known to have very strong regularities. For example, the Tully-Fisher relation and the Fundamental Plane have scatter in luminosity at the few tenths of a magnitude level. It seems unlikely that mass-to-light ratios among spirals or ellipticals of similar masses could be variable at the 50% level (as one can easily get within the framework of Conroy *et al.* 2009) without creating much more scatter in these relationships than observed.

The red sequence of galaxies has a tiny scatter in optical color, a few hundredths of a magnitude, even as it varies slowly across luminosity (at about -0.03 magnitudes in $g-r$ per unit absolute magnitude M_r; Blanton *et al.* 2003a). Thus, the uncertainties described above in stellar populations must at least cause little *variation* among galaxies within a given type and mass — otherwise (without some unusual set of coincidences) these regular patterns would instead have considerable scatter.

Similarly, as Schechter (1976) was among the first to show, the galaxy luminosity function has an abrupt exponential decay brighter than L_* (e.g. Blanton *et al.* 2003b). It might be that the galaxy stellar mass function has a slower cut-off, which is then accentuated by a sharply increasing stellar mass-to-light ratio with mass. However, if there is simply lots of *scatter* due to variations in IMFs (for example), then no stellar mass function could produce such a sharply falling luminosity function.

Metal-line indices exhibit similar behavior: they increase (especially Mg indices) strongly with galaxy mass (Worthey 1998). The quantitative interpretation of this trend is uncertain, but the qualitative one is clear: more massive galaxies contain more metal-rich, and very likely more α-enhanced, stars.

For this reason, the results of Kauffmann *et al.* (2003), as just one example, remain interesting even if their stellar ages and masses are grossly incorrect. It is difficult to understand given our other knowledge how they could be wrong in something other than a systematic offset with some slow mass dependence. Given this fact, many of their conclusions, on the relationships between environment, structure, mass, and age for example, or the relationships between recent star-formation rate, more ancient star-formation history, and environment, remain valid — if not in strict quantitative correctness, but in their impact on current galaxy formation models. In particular, we should not ignore the clues given to us by the studies of metallicity and age as a function of environment, with which we do not expect any of the systematic uncertainties to correlate strongly.

Given the regularities of galaxy spectra, one is tempted to try a different approach than fitting general models to individual spectra. I strongly endorse the approach of using an *extremely* general model, but requiring that only a small set (or small dimensional subspace) of possible star-formation histories explain *all* galaxies. This model forces the models to have regularity in parameter space that mirrors the regularity in observables. Without such enforcement, we might conclude that the narrow range of color and line indices of elliptical galaxies results from a wide variety of underlying histories, carefully tuned to create a narrow distribution in the observables.

Connolly *et al.* (1995) and other pioneers took a PCA approach to this sort dimensionality reduction. Of course, PCA is an entirely linear approach, and as such is not entirely efficient. In addition, it conflates the effects of regularity within the model parameters and within the model spectra themselves (which are all based on stellar spectra, which as Ricardo Schiavon pointed out in the question period, are all ultimately just due to the combined effects of three parameters: "temperature, temperature, and temperature"). Blanton & Roweis (2007) show that a few model star-formation histories (non-negatively combined) can explain well the features of many spectroscopic and photometric results. Vanderplas & Connolly (2009) look purely at the observations, but use a nonlinear method to very efficiently describe the space.

7. Elliptical galaxies

Elliptical galaxy spectra, because they are known to be (mostly) old stellar populations, and (mostly) dust-free, have formed a special topic in this area for decades. Thus, I will say a few words about recent results based on massive surveys.

Unfortunately, in the context of such surveys, ellipticals are hard to identify unambiguously. The red sequence of galaxies consists primarily of S0 and Sa galaxies except at its highest luminosities, with Es accounting for 40% or so. Since in gross structural terms Es are similar to S0s and Sa galaxies — high concentration, with the same size-luminosity relationship (Blanton & Moustakas 2009) — cataloged photometric measurements allow one only to define elliptical galaxy populations that have contamination rates of about 20%. The identifiable interlopers tend to be barred S0s or spirals with strong dust lanes (Zhu, Blanton & Moustakas in preparation). Thus, many of the results taken from massive surveys need to be treated with a grain of salt: there are considerable uncertainties simply due to not being able to select elliptical galaxies automatically in a perfect manner.

Nevertheless, it is worth examining what such studies have learned. One of the best recent analyses has been that of Graves *et al.* (2009), who used the statistical power of the SDSS by combining many individual SDSS spectra into higher signal-to-noise stacked spectra. They combined galaxies in similar regions of the Fundamental Plane space of parameters, choosing galaxies as a function of σ and R_e within three slabs higher, equal, and lower surface brightness than the main Fundamental Plane. As expected, higher velocity dispersion galaxies yielded weaker Hβ absorption (older) and stronger iron indicators. They furthermore found that iron indicators were generally stonger and ages younger for higher surface brightness galaxies. When interpreted in terms of stellar populations models, these results also indicated that the α-enhancement of the higher surface brightness galaxies is strong.

Meanwhile, Graves *et al.* (2009) found very little relationship between *size* and stellar populations once the σ dependence was accounted for. These results put fascinating new constraints on star-formation histories of ellipticals: somehow they must be closely related to velocity dispersion but not to the total mass of the galaxy.

With stellar population analysis, investigators have been able to examine the role that stellar mass-to-light ratio variations may play in the tilt of the Fundamental Plane. Of course, conclusions in this case do rely on systematic effects such as the IMF to be a small function of mass. But if the IMF is nearly constant, the conclusion from a number of recent analyses is that the stellar mass-to-light ratios are not increasing at a sufficient rate with mass to fully or even substantially explain the tilt (Padmanabhan *et al.* 2004, Trujillo *et al.* 2004, Proctor *et al.* 2008). Since non-homology appears also not to be able to explain this effect (Bolton *et al.* 2008, Cappellari *et al.* 2006), it appears likely that more massive elliptical galaxies have a larger dark matter fraction.

A number of workers have examined how the stellar populations of ellipticals varies with environment, yielding somewhat contradictory results. Generally, the environmental dependence is *small*. Among the largest reported effects is that of Bernardi *et al.* (2006), who find a 0.1 mag surface brightness shift between their highest and lowest density subsamples. Together with their spectroscopic constraints, this result led to the conclusion that the former were formed about 1 Gyr earlier than the latter. Similarly, Thomas *et al.* (2005) report a larger difference in age between field and cluster ellipticals. However, the optical results of Trager *et al.* (2008) suggest that Coma galaxies are similar in age to field ellipticals, and mid-IR indicators lead to the same conclusions (Bressan *et al.* 2006, Bregman *et al.* 2006).

Motivated by this cacophony in the literature, some collaborators and I have waded into this subject, hopefully to not just add to the noise (Zhu, Blanton & Moustakas in preparation). After an objective *preselection* of SDSS galaxies within $z < 0.05$, one of us (Zhu) looked at the remaining 2500 galaxies and trimmed the 20% of remaining outliers. Then, we classified the galaxies according to velocity dispersion and environment, and stacked galaxy spectra within these classes. We find that indeed at fixed velocity dispersion the differences in elliptical galaxy spectra are small but detectable. In the absorption index measurements, the differences tend to be tiny shifts well below the dispersion in individual measurements. However, the isolated galaxies show a greater tendency to have detectable emission and show a (very slightly!) bluer continuum, especially below 4000 Å. These signatures appear to be consistent with the results of Schawinski *et al.* (2007), revealing a tendency for some recent star-formation in field ellipticals.

Again, some of these results, particularly those which span different mass populations, may be driven by hidden correlations of the IMF or fraction of hot HB stars with (say) environment, surface brightness or mass. We cannot at this time rule such possibilities out. However, efforts are ongoing to try to obtain sufficient independent constraints on the star-formation histories to pin down these possibilities. As one example, Panter *et al.* (2008) compare their *archeological* inferred star-formation history with look-back studies of star-formation in high redshift surveys.

8. What can new large surveys give us?

The next decade of large surveys astronomy is surprisingly not focused on spectroscopic observations at all, much less on ones motivated to better understand stellar populations. While the middle of next decade will yield a series of increasingly deeper wide-field surveys from Pan-STARRS, the Dark Energy Survey, HyperSuprimeCam and ultimately LSST, there are fewer efforts ongoing in spectroscopy.

In the near-term, the Baryon Oscillation Spectroscopic Survey (BOSS) is a cosmologically motivated survey using a refurbished spectrograph on the SDSS 2.5m telescope, that will take spectra of 1.6 million luminous galaxies (many of them red). BOSS exemplifies the promises and perils of understanding galaxy formation through stellar populations from upcoming galaxy surveys. It is motivated to achieve as large a volume as it can to measure the baryon oscillation feature in the galaxy two-point statistics, driving it to a strategy in which many of its spectra will be quite low signal-to-noise. Thus, while stacking spectra will still yield spectacular results regarding the evolution of these massive galaxies over time, the individual spectra will in most cases be extremely hard to use.

Target selection is another important aspect of such surveys that can easily be overly driven by cosmological parameter requirements. Measuring cosmology requires large volumes and often would favor strongly biased tracers — massive, luminous galaxies are therefore favored. In the case of BOSS, for the distant sample it turns out to be possible to at least take a nearly stellar-mass-limited selection as a function of redshift, and to include luminous blue galaxies in target selection. Future cosmological surveys would do well to make similar adjustments to strategy that might punish cosmological constraints slightly, but would allow galaxy formation science to much more fruitfully use the data.

In a similar vein, it is important to maintain spectrophotometric calibration, highly important for galaxy evolution but not as much for cosmology. A ruthless optimization of resources would minimize calibration in future cosmological surveys (as was done, for example, in DEEP2; Davis *et al.* 2003). Nevertheless, it would be a shame to forfeit the gold mine of information about galaxies such surveys would otherwise yield.

However, the requirements of cosmological surveys necessitate a continually increasing volume, which motivates taking wider and wider areas of sky to maintain good window functions and to maximize observing efficiency — given the same volume distributed in a wide solid angle and one distributed in a narrow cone, it is more observationally efficient to map the former than the latter. Meanwhile, the requirements for understanding galaxy formation ultimately require only a minimum volume to represent a fair sample, and improvements over that require a depth in redshift to constrain evolution. Furthermore, there is a minimum data quality required that is much greater than for cosmological surveys. These competing requirements ultimately will drive a wedge between surveys that seek to maximize cosmological constraints and those that are focused on galaxy evolution.

New large surveys that would have a significant impact of galaxy evolution studies would include expanded versions of the VVDS and zCOSMOS surveys, to embrace fair-sample-sized volumes. Ground-based near-infrared surveys would allow one to probe a series of redshift shells *each* as large as the SDSS Main sample, out to $z \sim 2$, with rest-frame optical coverage (Bell *et al.* 2009). Given recent discoveries regarding the assembly of elliptical galaxies at those epochs such a survey would clearly be an essential measurement of a active and violent time in galaxy evolution (e.g. van Dokkum 2008).

A completely different tack that some collaborators and I have taken recently is the PRIMUS survey (Cool, Coil, Blanton, Moustakas, Zhu, Wong & Eisenstein, in preparation). This survey uses a prism-plus-mask configuration on IMACS at the Baade 6.5m telescope at Las Campanas. We mapped the Universe with 1% redshifts out to $z \sim 0.9$, over 10 square degrees. By using a low-dispersion prism, we can observe more than 2000 galaxies at a shot, and over 30 or so nights took 300,000 spectra. While the low resolution spectra themselves yield little stellar population information, the map provides fodder for efficient follow-up observations on galaxies across redshift and environment. Furthermore, we have chosen areas of the sky covered by GALEX and Spitzer, allowing us to better determine the redshift evolution of the rest-frame galaxy properties such as color and luminosity.

9. Final comments

In the above I have been critical of stellar populations, while using their conclusions in selected ways. I should conclude by saying that understanding stellar populations is *critical* to understanding galaxy evolution. While for the moment we can content ourselves with qualitative statements and detecting trends, the time draws near in the next decade or two when galaxy formation theory will make far more specific predictions. Therefore, understanding stellar evolution in detail, including the energetically important late phases of stars, will only become more important over time.

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