Essay:
Extragalactic Stellar Populations

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It appears to me that we are standing at the brink of a quantitative revolution in our understanding of extragalactic stellar populations. I argue here that support for a small number of infrastructural areas will yield amazing scientific progress in the next decade.

The two areas that stand out most of all are (1) the observation of precise stellar evolution fundamentals: the masses of stars, the distances of star clusters, and the chemical abundances in interesting stars, and (2) the theory of stellar atmospheres, including work on line lists via the study of many-body quantum physics for atoms and molecules. For (1) the most appropriate action seems to be support of astrometry, with SIM the only mission on the horizon capable of helping substantively. For (2), laboratory and theoretical work should be explicitly supported.

I strongly suspect that it is these areas that will benefit the world of galaxy evolution the most! For, underneath it all, what one wants is the age structure and chemical fingerprint of galaxies throughout the universe, and the barriers to this have far more to do with understanding stars and stellar evolution than with collecting more and more distant photons.

1. Ages of Galaxies

As a stand-in for related problems, I use the *derivation of mean stellar ages* of high-redshift galaxies as a substantive example. Obviously, other objects could be chosen, statistical methods employed, or other derived quantities targeted, but the example should suffice for this white paper.

> There are many stellar population models available today (e.g. Blakeslee et al. 2001; Bressan et al. 1994; Bruzual & Charlot 1993; Dorman et al. 1993; Kodama & Arimoto 1997; Liu et al. 2000; Salasnich et al. 2000; Schulz et al. 2002; Schiavon et al. 2002a,b; Tantalo et al. 1998; Vazdekis et al. 1997; Worthey 1994). Unfortunately, to use such a model is to enter a confusing world of dubious quality control and conflicting results. These days, with both isochrone sets and synthetic fluxes now electronically available, it is a matter of a few days of programming to unite the two to produce a model for integrated light. Crazy results are easy to generate because of the proliferation of hastily constructed models plus misuse of properly constructed ones. The main causes for discrepancies in broad-band color space are the stellar evolution ingredients (Worthey 1994; Charlot et al. 1996; Yi 2003). That is, the number, temperatures, and luminosities of the stars are a bigger uncertainty than the observational character of the stars themselves. At higher spectral resolution, however, the detailed, element-by-element chemical mixtures of galaxies, if unaccounted for, dominates the error budget (Worthey 1998).

I would hope that, in the next decade, we could beat the zero point error down to *5% or better in the absolute ages* of star clusters and therefore isochrone models. In order to do that, we need to greatly reduce the star cluster distance uncertainty. Chaboyer (1995) investigated the star cluster age scale, finding that the luminosity of the main sequence turnoff was the best age indicator. His results still hold basically true. The error on the luminosity is dominated by distance uncertainties and the age uncertainty is on the order of 15% from physics alone, and of order 25% when observational difficulties are thrown in, mostly dominated by distance scale uncertainty and secondly by chemical abundance uncertainty.

I would comment on the latter and follow Bengt Gustafsson to boldy propose *1% stellar abundances* as a reasonable 2020 goal. To get to such a dizzying tolerance requires us to get a lot of things more precisely right about stellar atmospheres than we presently do. Line lists, more physical line profiling, and convection are at the top of the to-do list. If we achieve this, however, it is certain that amazing new chemical structures will emerge.

I have been working on the *downstream* uncertainties of this game for some time (e.g. Worthey 1998, Serven et al. 2005, Dotter et al. 2007). The following table illustrates some typical results for error propagation.

Propagated Model-Derived Galaxy Age Shifts
(Compare to 2020 Target Age Uncertainty of 5%.)

Quantity	Varied by	Propagated Age Shift
Overall [Z/H]	20%	30%
Metallicity Spread	3% - 10% metal poor fraction	15%
Blue Stragglers	Range found in Milky Way	12%
[C/U]	0.2	40%
[N/U]	0.2	10%
[O/U]	0.2	13%
[Fe/U]	0.2	17%
AGB Stars	A Factor of Two	3%
Hor. Branch Shape	Extreme HB on/off	4%
IMF	+/- 1 in power law slope	13%

Notes: “Metallicity spread” modifies the breadth of the abundance distribution between the too-broad “Simple Model” shape and the observed, narrower spread, which so far looks fairly universal. “AGB” is the late-stage helium burning asymptotic giant branch, and includes all post-horizontal branch phases. The “Extreme Horizontal Branch” is an oft-seen collection of 25000 K stars with small hydrogen envelopes that are probably responsible for the “UV bump” phenomenon in elliptical galaxies (Burstein et al. 1998)

Some of the age-numbers in the last column look fairly scary, but there there really isn't anything there that cannot be beaten down with suitable hard work. Disentangling C, N, and O is still unsolved, but progress is rapid. With commensurate progress in stellar abundances, there seems to be no barrier to extending a 5% age uncertainty to the entire universe of galaxies by 2020.

2. Roadmap to New Age-Chemistry Vistas

1. Fix the cluster distance issue. I think SIM can solve that. GAIA does not have the range to reach key calibrating clusters at metallicities other than solar.
2. Fix the line list. Half the lines in the solar spectrum remain unidentified (It is known that most of them are due to upper transitions in Fe atom, but their wavelengths are not predicted with sufficient accuracy to actually tell which is which.) The state of many molecular line lists is very primitive. I think this requires a high-level recommendation such as the decadal committee can provide.
3. Fix a few things regarding stellar atmospheres and convection. I do not have as clear an idea of how to proceed in this regard. Asplund and collaborators (e.g., Asplund et al. 2005) have clearly achieved a quantum leap, but no domestic groups have sprung up to compete. I think a more infrastructural approach to maintain the health of the mundane body of astrophysics is needed.

3. Appendix: Other Applications of Stellar Population Models

Stellar population models use stellar evolutionary isochrones plus stellar flux information summed over a single-burst stellar population to give integrated-light observables like colors and spectral line strengths. They have a variety of ingredients, but always two main components: stellar evolution to populate the stars in the log **L**, log **T** diagram, and stellar observable properties (colors, spectra, etc.) so that the theory can be related to observation. I make little distinction between isochrones and integrated-light models since the latter are the former under an integral sign.

To condense the "modern era" of stellar populations to few sentences, Bruzual (1981) showed how stellar evolution could be used to predict the colors and luminosities of high-redshift galaxies. At about the same time, O'Connell (1980) showed that age information could be extracted from a single integrated light spectrum, but only if the metallicity was known in advance. Improvements in stellar evolution theory (e.g. VandenBerg & Bell 1985) bolstered hopes that precision age information could be extracted from cluster color-magnitude diagrams, and allowed the addition of metal abundance as a parameter in integrated light models. With metallicity added and with the addition of spectral absorption feature indices (Worthey 1994) a method was developed to extract a mean age and metallicity simultaneously from Balmer and metallic absorption features measured in a single integrated light spectrum of objects with ages between ~0.5 and 14 Gyr. Leitherer (1995a,b) pioneered work on young populations, where the main degeneracy is between age and slope of the initial mass function (IMF), and Leonardi & Rose (1996) found a way to disentangle burst age from burst mass in post-starburst objects.

The following incomplete list gives a flavor for the multiplicity of applications that could be addressed by more flexible, more accurate models that should flow from the more fundamental, infrastructural support that I suggest in this essay.

- Open and globular cluster ages from color-magnitude diagram studies.
- Star formation histories of local dwarf galaxies are derived from color-magnitude diagram decomposition, including the chemical history in favorable cases.
- Star formation history of the Milky Way through star counting.
- Extragalactic globular cluster systems within ~10,000 km/s have color distributions that can be statistically related to galaxy formation scenarios, and cluster systems within ~1500 km/s can be studied spectroscopically to get individual ages and metal abundances for each. By 2020, this range will have extended substantially.
- Light/heavy element ratios, especially in elliptical galaxies, are known to vary from the solar ratios. Measurement of abundance ratios is much more accurate when the models can be adjusted for different chemistries. First-generation models should be coming out very soon (Dottter et al. 2007).
- Surface-brightness fluctuation magnitudes remain an exciting distance measurement tool. Stellar population models give a-priori values that skip almost all distance-ladder steps. The same models are the only way to estimate k-corrections for SBF and thus revitalize the peculiar-motions field as accuracies increase.
- Post-starburst objects give crucial insight into galaxy cluster formation and rely heavily on stellar population models.
- Starburst objects are studied with the aid of stellar population models.
- Quasars and AGN occasionally have to have the starlight subtracted in order to reveal more about the nebular diagnostics and synchrotron continuum. Conversely, the hosts of these powerful objects can be studied through analysis of their starlight using stellar population models.
- Cosmological studies of galaxies utilize stellar population models to account for stellar population evolution and k-corrections as a function of lookback time.
- Spectroscopic studies of individual galaxies to **z**>1 are now possible with large telescopes, with abundance and age measurements possible through stellar population models in cases of sufficient signal.
- Chemo-dynamical galaxy evolution models (N-body, hydro, SPH) are coming to rely more and more on stellar population models so that predictions can be compared with observations.
- Chemical evolution, typified by the G-dwarf problem, can be extended to external galaxies as far as the Virgo cluster via color-magnitude diagrams of the red giants, interpreted through stellar population models.

Asplund, M.; Grevesse, N.; Sauval, A. J.; Allende Prieto, C.;Blomme, R. 2005, Line Formation in Solar Granulation. VI. [C I], C I, CH and C_2 Lines and the Photospheric C Abundance, A&A, 431, 693
Blakeslee, J. P., Vazdekis, A., & Ajhar, E. A. 2001, Stellar Populations and Surface Brightness Fluctuations: New Observations and Models, MNRAS, 320, 193
Bressan, A., Chiosi, C., & Fagotto, F. 1994, Spectrophotometric Evolution of Elliptical Galaxies. 1: Ultraviolet Excess and Color-Magnitude-Redshift Relations, ApJS, 94, 63
Bruzual, A., G. 1981, Spectral Evolution of Galaxies, Ph. D. Thesis, Univ. of California, Berkeley
Bruzual, A., & Charlot, S. 1993, Spectral Evolution of Stellar Populations Using Isochrone Synthesis, ApJ, 405, 538
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, The Far Ultraviolet Spectra of Early-type Galaxies, ApJ, 328, 440
Chaboyer, B. 1995, Absolute Ages of Globular Clusters and the Age of the Universe, ApJ, 444, L9
Charlot, S., Worthey, G., & Bressan, A. 1996, Uncertainties in the Modeling of Old Stellar Populations, ApJ, 457, 625
Dorman, B., Rood, R. T., & O'Connell, R. W. 1993, Ultraviolet Radiation from Evolved Stellar Populations. I. Models, ApJ, 419, 596
Dotter, A. Chaboyer, B., Ferguson, J. W., Lee, H.-c., Worthey, G., Jevremovic, D., Baron, E. 2007, ApJ, 666, 403
Kodama, T., & Arimoto, N. 1997, Origin of the Colour-Magnitude Relation of Elliptical Galaxies, A&A, 320, 41
Leitherer, C., & Heckman, T. M. 1995a, Synthetic Properties of Starburst Galaxies, ApJS, 96, 9
Leitherer, C., Robert, C., & Heckman, T. M. 1995b, Atlas of Synthetic Ultraviolet Spectra of Massive Star Populations, ApJS, 99, 173
Leonardi, A. J., & Rose, J. A. 1996, The Ages of Starbursts in Post-Starburst Galaxies, AJ, 111, 182
Liu, M. C., Charlot, S., & Graham, J. R. 2000, Theoretical Predictions for Surface Brightness Fluctuations and Implications for Stellar Populations of Elliptical Galaxies, ApJ, 543, 644
O'Connell, R. W. 1980, Galaxy Spectral Synthesis. II - M32 and the Ages of Galaxies, ApJ, 236, 430
Salasnich, B., Girardi, L., Weiss, A., & Chiosi, C. 2000, Evolutionary Tracks and Isochrones for Alpha-Enhanced Stars, A&A, 361, 1023
Schiavon, R. P., Faber, S. M., Castilho, B. V., & Rose, J. A. 2002a, Population Synthesis in the Blue. 1. Synthesis of the Integrated Spectrum of 47 Tucanae from its Color-Magnitude Diagram, submitted to ApJ, astro-ph/0109364
Schiavon, R. P., Faber, S. M., Rose, J. A., & Castilho, B. V. 2002b, Population Synthesis in the Blue. 2. The Spectroscopic Age of 47 Tucanae, submitted to ApJ, astro-ph/0109365

Schulz, J., Fritze – v. Alvensleben, U., Moller, C. S., & Fricke, K. J. 2002, Spectral and Photometric Evolution of Simple Stellar Populations at Various Metallicities, A&A, 392, 1

Serven, J., Worthey, G., Briley, M. M. 2005, ApJ, 627, 754

Tantalo, R., Chiosi. C., Bressan, A., Marigo, P., & Portinari, L. 1998, Spectrophotometric Evolution of Elliptical Galaxies. III. Infall Models with Gradients in Mass Density and Star Formation, A&A, 335, 823

Vandenberg, D. A., & Bell, R. A. 1985, Theoretical Isochrones for Globular Clusters with Predicted BVRI and Stromgren Photometry, ApJS, 58, 561

Vazdekis, A., Peletier, R., Beckman, J. E., & Casuso, E. 1997, A New Chemo-Evolutionary Population Synthesis Model for Early-Type Galaxies. II. Observations and Results, ApJS, 111, 203

Worthey, G. 1994, Comprehensive Stellar Population Models and the Disentanglement of Age and Metallicity Effects, ApJS, 95, 107

Worthey, G. 1998, Abundance Ratio Trends and Nucleosynthesis in Elliptical Galaxies and Spheroids, PASP, 110, 888

Yi, S. K. 2003, Uncertainties of Synthetic Integrated Colors as Age Indicators, ApJ, 582, 202