The 2010 May Symposium will bring together two communities of astronomers, those studying resolved stellar populations in the nearby Universe and those focusing on the properties and evolution of stellar populations in the highest-redshift systems. Review and contributed talks will illustrate the latest observational and theoretical views on the processes that lead to the formation of stellar populations and their stellar, chemical, and dynamical evolution. The link between star clusters and galaxies, and their role as building blocks of more massive systems will also be discussed. By addressing the limitations of our knowledge of resolved populations, the symposium will improve our understanding of what can be confidently said about galaxy properties across cosmic time, including new observations ranging from systems at intermediate redshifts, when star formation peaks, to the first few billion years of the Universe.

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Stellar Populations in the Cosmological Context
STScI May Symposium (2010)

SED fitting with Markov Chain Monte Carlo: comparison of results with grid-based methods for a sample of Lyman Alpha Emitters at z = 3.1

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We present the results of multiwavelength Spectral Energy Distribution fitting of a complete sample of 162 Lyα-emitting (LAE) galaxies at z = 3.1 discovered in deep narrow-band imaging of the Extended Chandra Deep Field South from the MUSYC Collaboration (PI Gawiser). We divide the sample into two sub-samples, “IRAC-detected” and “IRAC-undetected”, according to whether or not the single objects are detected at 2-σ in the IRAC 3.6 µm band. The properties of these subsamples of LAEs, computed via a traditional grid-based method of best-fit search, were presented in (Lai et al 2008, ApJ 674, 70). We apply our new MCMC SED fitting method to the same sample, showing that not only we are able to recover the same best fit values, but we gain a lot of additional information on correlation between parameters; as a consequence, we have a better understanding of uncertainties.

Our MCMC algorithm allows for a tremendous saving of CPU time with respect to traditional grid-based methods. For example, the fit presented below required 8 hours of CPU time on a standard desktop, with continuous sampling of parameter values, a factor of 50 times faster than a brute-force approach sampling each parameter at 100 different values. Furthermore, the higher the dimensionality of the sampled parameter space, the more dramatic the savings of CPU time are with respect to a grid-based method. This enables more detailed models to be fit, including variation in redshift versus a best-fit photo-z, multiple stellar populations, and realistically complex star formation histories. This approach will illuminate degeneracies missed by oversimplified models and therefore greatly reduce systematic errors on SED parameters (Acquaviva et al. 2010, in prep.) We are currently in the process of applying this method to a new sample of 250 LAE emitters at z = 2.1 (Guaita et al 2010, in prep.)

Left - Right: The 1 and 2-dimensional marginalized posterior probability (likelihood, “χ”) of the three parameters of our MCMC SED fit, for the IRAC-undetected subsample of LAEs at z = 3.1 LAE sample. Contours in the plots show the 68 and 95% confidence levels on the parameters. Our findings for the best fit values are in perfect agreement with those obtained via a grid-based SED fit method which uses the same parameters and stellar evolution models (Lai et al 2008). However, the MCMC algorithm is faster and allows us to collect information on the average expectation values of the parameters, to easily compute uncertainties in a Bayesian fashion, and informs us on degeneracies between parameters.
The Formation and rapid disruption of stellar clusters
Nate Bastian (Exeter)

Co-authors: Eli Bressert, Gelys Trancho, Mark Gieles, Iraklis Konstantopoulos, Henny Lamers, Simon Goodwin

Do all stars form in clusters? The answer to this question is surprisingly complex and resolves around a precise definition of what is meant by a “cluster”. Defining open and globular clusters is relatively straightforward, however the cites of on-going star-formation are much more complex. I will present the first unbiased study of nearly all star-formation within 500pc of the sun based on a collection of surveys carried out with the Spitzer Space Telescope. By creating the surface density distribution of all identified young stars, we find that their exists a continuous distribution of surface densities from <0.1 stars/pc$^{-2}$ to a few hundred stars per square parsec. This shows that there does not exist two distinct modes of star formation (i.e. clusters/distributed), but rather that star-formation proceeds hierarchically within these regions (left panel). Previous results that suggested such a dichotomy were based on K-band number counts which were strongly biased towards high-density regions. Open clusters appear to be simply the high density tail of this distribution which have been able to remain bound.

I will also review the early stages of cluster evolution (once a bound structure exists) and destruction. I will focus on recent work cluster populations to constrain cluster disruption. In particular, I will highlight the importance of assumptions on the star-formation history of galaxies in the interpretation of cluster populations (right panel).

Left: The surface density distribution of nearly all YSOs with 500pc of the sun based on a collection of Spitzer surveys. Note the continuous distribution indicating the lack of multiple distinct ‘modes’ (i.e. clustered or distributed) of star-formation. The red dashed line is a log-normal fit the data, which is consistent with expectations of a hierarchical distribution.

Right: The age distribution of clusters in the Antennae galaxies (Whitmore et al. 2007) along with a model of the SFH during the interaction by Mihos et al. (1993). Note that other than the most recent 10 Myr, the cluster age distribution is well fit by the models.

Bressert, Bastian, Gutermuth & the Gould Belt Team, MNRAS submitted
Galactic Archaeology: The Lowest Metallicity Stars

Timothy C. Beers (Michigan State University)

Co-authors: Young Sun Lee, Deokkeun An, Daniela Carollo

The lowest metallicity stars in the Galaxy preserve our best snapshots of the chemical elements formed in the Big Bang, and in the very first generations of (presumably) massive stars that theory tells us formed shortly thereafter. Over the past several decades, dedicated searches for these objects have identified at least a handful of stars with metallicities [Fe/H] less than one hundred thousandth the solar abundance, and approaching one millionth solar. Astronomers are also learning how better to identify and mine these fossils of creation in the future, based on the apparent association of the lowest metallicity stars with the outer-halo component of the newly recognized inner/outer structure of our Galaxy. In this review, I summarize the current state of affairs, consider current evidence for the multiple metallicity distribution function of the dual halo, and point toward the new survey efforts to begin in the near future.

Left: The "as-observed" metallicity distribution function (MDF) of stars with spectroscopic determinations of metallicity [Fe/H] < -2.0, from the SDSS/SEGUE surveys. Note the possible presence of deviations from a continuous function around [Fe/H] ~ -2.5, suggesting greater contribution from outer-halo stars.

Right: Photometric estimates of metallicity, based on the full set of ugriz filters, for the SDSS equatorial stripe, including stars up to 30 kpc from the plane. The normalization is such that each horizontal line of pixels represents an independent MDF (and does not indicate the relative number of stars in the vertical direction). This map demonstrates the presence of contributions from the thin disk, thick disk, metal-weak thick disk, inner halo, and outer halo.

Beers, T.C., IAU Symposium 265, p. 453
A Comprehensive Analysis of Uncertainties Affecting the Stellar Mass - Halo Mass Relation for 0<z<4

Peter Behroozi (Stanford)

Co-authors: Charlie Conroy and Risa Wechsler.

We conduct a comprehensive analysis of the relationship between central galaxies and their host dark matter halos, as characterized by the stellar mass - halo mass (SM-HM) relation, with rigorous consideration of uncertainties. Our analysis focuses on results from the abundance matching technique, which assumes that every dark matter halo or subhalo above a specific mass threshold hosts one galaxy. We provide a robust estimate of the SM-HM relation for 0<z<4 and discuss the quantitative effects of uncertainties in observed galaxy stellar mass functions (including stellar mass estimates and counting uncertainties), halo mass functions (including cosmology and uncertainties from substructure), and the abundance matching technique used to link galaxies to halos (including scatter in this connection). We also provide a detailed comparison to other methods, and we discuss the most effective ways for new experiments to reduce the uncertainties present in the current analysis. These results will provide a powerful tool to inform galaxy evolution models.

Left: The ratio of stellar mass to halo mass, as a function of halo mass and redshift, with full error estimates.

Right: The ratio of stellar mass to halo mass at z=0.1, compared to results from ten other papers. The light shaded region shows our estimate for the statistical + systematic errors; the dark shaded region shows our estimate for the statistical errors alone.

The Galactic Bulge and Thick Disk

Thomas Bensby (ESO, Chile)

Co-authors: S. Feltzing, J.A. Johnson, J. Melendez, A. Gould, M. Asplund, A. Alves-Brito, M.S. Oey, D. Yong, S. Lucatello

The Galactic bulge and the Galactic thick disk are two major stellar components of the Milky Way galaxy. Recent high-resolution spectroscopic studies have shown that they might be intimately connected. Deciphering and understanding this possible connection will give many valuable pieces to the puzzle of galaxy formation in general.

The first figure shows the [Ti/Fe]-[Fe/H] abundance trend for 16 dwarf stars in the Bulge (big filled circles; 13 from Bensby et al. 2010a, and 3 new ones observed in April 2010) that were observed with high-resolution spectrographs while they were optically magnified during microlensing events. This sample of microlensed Bulge dwarfs is compared to a new sample of 700 nearby F and G dwarf stars in the Galactic disk (Bensby et al., in prep.), analysed with the exactly same methods, enabling truly differential comparisons between the different stellar populations. Thick disc stars are shown as small circles, and the solid line is the running median of the shown thick disc sample, and the dashed line the running median of the (not shown) thin disc sample from Bensby et al. (in prep).

Next, we have now observed a sample of 44 K giants in the inner Galactic disk, located 4-7 kpc from the Galactic centre (see Bensby et al. 2010b). A majority these can be classified as thick disk stars (both kinematically and chemically). The figure shows the [Mg/Fe]-[Fe/H] abundance trend for these inner disk giants (black filled circles) together with Bulge giants (red diamonds), nearby thin disk giants (green empty circles); and nearby thick disk giants (blue stars), all from Alves-Brito et al. (2010), and that have been analysed using the exact same methods as the inner disk giants.

Our main results are:

1. Based on dwarf stars only we see that the Bulge abundance trends agree very well, at subsolar [Fe/H], with those of the nearby thick disk.
2. Now for the first time, based on analysis of giant stars, we have shown that the abundance trends of the inner thick disk is similar to the nearby thick disk in the solar neighbourhood, and also similar to the Bulge (at subsolar [Fe/H]).
3. This could indicate that the metal-poor parts of the Bulge are of secular origin, formed from inner disk material, and that the metal-rich parts of the Bulge have a different origin. This could possibly be accreted material.

Young Stellar Populations in the Local Group:
a treasury HST and GALEX study.

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Wide-field far-UV and near-UV GALEX imaging of Local Group galaxies affords a global, deep census and characterization of their recent star-formation sites, across a wide variety of environmental conditions. The resolved stellar constituents of selected star-forming sites are studied with HST multi-band imaging (Bianchi's treasury program 11079). The HST results provide the key for the interpretation of GALEX data covering the whole extent of the Local Group galaxies, and of measurements available for hundreds of nearby galaxies beyond the Local Group, shedding new light on the process of star formation in differing conditions, and on the interplay between star formation and interstellar dust.

Three galaxies of the sample

We acknowledge support from HST grant GO-11079 and from GALEX
Stellar Populations of High-Redshift Star-Forming Galaxies Using Rest-frame Optical and UV Imaging

Nicholas Bond (Rutgers University)

Co-authors: Eric Gawiser, Caryl Gronwall, Robin Ciardullo, John Feldmeier, Anton Koekemoer

We present a rest-frame optical and rest-frame ultraviolet analysis of stellar populations in 160 $2 < z < 3.5$ Star-Forming Galaxies (SFGs) in the Extended Chandra Deep Field South, including 39 Lyman Alpha Emitters. Using Hubble Space Telescope images taken as part of the Hubble Ultra-Deep Field survey, the WFC3 Early Release Science program, and the Great Observatories Origins Deep Survey, we analyze the sizes and light profile shapes of SFGs in BV1zYJH images, comparing the rest-ultraviolet and rest-optical morphological properties on an object-by-object basis. The physical sizes of SFGs range from $< 1$ kpc to $\sim 5$ kpc, while LAEs are typically $< 1.5$ kpc in size in all of the observed filters. Many objects display a characteristic "two-clump" structure, in which each clump is dominated by stellar populations of different ages. This is supported by the distribution of internal color dispersions, which shows an excess of high-dispersion objects as compared to a population of "normal" galaxies at $2 < z < 3$.

**Left:** Internal color dispersion vs. rest-frame UV-optical color for a sample of SFGs in the WFC3 ERS. High internal color dispersions suggest the presence of an older stellar population in addition to the young population seen in the rest-frame UV.

**Right:** A subset of SFGs with internal color dispersion $> 0.1$, comparing rest-frame UV (observed I-band) morphologies on the left to rest-frame optical (observed H-band) morphologies on the right. Their morphologies are highly suggestive of mergers-in-progress. The dimensions of the cutouts are 5'' x 5'' (40 kpc x 40 kpc).
Are the Ultra-Faint Dwarfs Fossils of the First Galaxies?

Mia S. Bovill (University of Maryland)

Co-author: Massimo Ricotti

We present the first results from a new set of CDM simulations which suggest that a fraction of the recently discovered ultra-faint dwarf population consists of the fossil remnants of primordial galaxies that formed the majority of their stars before reionization. Our new simulations allow us to map the distribution of fossil and non-fossils dwarfs in the Local group and compare the simulated maps to observations. We show good agreement between our simulations and observations of the ultra-faints in both their radial distribution within the Milky Way virial radius and their stellar properties. However, the properties of the faintest ultra-faint satellites found within 50 kpc of the Galactic Center have half light radii too low for them to be equated with a population of well preserved primordial fossils. Based on their other stellar properties, these Willman I type objects likely originated as more massive fossils, which have been modified by tidal effects.

In addition, we expand the discussion, begun in Bovill & Ricotti (2009), of the hereto undetected population of dwarfs with surface brightnesses below SDSS limits. The fossils comprising this mega-faint population would have higher M/L and lower [Fe/H] than the ultra-faints, but similar distributions in half light radii and stellar velocity dispersions. We expect an even higher fraction of the undetected dwarfs to be primordial fossils when compared to the ultra-faint and classical populations.

Above: Distributions half light radii (bottom) and average surface brightness (top) as a function dwarf luminosity (left), M/L and stellar velocity dispersion (center) and of Fe abundance as a function of luminosity (right). The properties of the classical dIrrs (asterisks), dEs (crosses), Milky Way dSphs (closed circles), M31 dSphs (closed triangles) and ultra-faint Milky Way dwarfs (open circles), and ultra-faint M31 dwarfs (open triangles) are plotted over those of our simulated fossil dwarfs (blue and red contours). The blue contours show the fossils detectable by the Sloan and the red contours the properties of the fossils which remain undetectable. The filled green circles are the “Willman I” type Milky Way ultra-faints. The lines on the left plot show the detection limit of SDSS (solid) and the expected trend when only the classical dwarfs are considered (dashed). The observational data we used is summarized in Bovill & Ricotti (2009).

In the last few years we have seen considerable progress in the quality and extent of data sets used as ingredients in population synthesis models. Stellar evolution models with updated input physics for stars up to 15 Msun have been computed by Bertelli et al. (2008), Marigo & Girardi (2007), and Marigo et al. (2008) provide a semi-empirical prescription to follow the evolution of TP-AGB stars that includes several important theoretical improvements over previous calculations. The Marigo & Girardi prescription has been calibrated using carbon star luminosity functions in the Magellanic Clouds and TP-AGB lifetimes (star counts) in Magellanic Cloud clusters. Bertelli et al. use different TP-AGB tracks, also based on the Marigo & Girardi prescription, but extrapolated to different chemical compositions of the stellar envelope. These sets of TP-AGB tracks are uncalibrated, as pointed out by Bertelli et al., since no attempt was made to reproduce the available observations. Numerous stellar spectral libraries are available and ready to use for population synthesis models. On the theoretical side, spectral libraries of theoretical model atmospheres by Lanz & Hubeny (2003, 2007), Martins et al. (2005), Rodríguez-Merino et al. (2005), Coelho et al. (2007), and Aringer et al. (2009) represent important improvements over the Westera et al. (2002) BaSeL 3.1 atlas, both in spectral resolution and coverage of physical parameters. Similarly, the IndoUS, MILES, and HNGSL libraries provide high quality empirical spectra with excellent coverage of parameter space in the optical and near UV range for stars of different metallicities not far from Zsun, increasing the number of available spectra by a factor of roughly 20 with respect to the STELIB library. IR spectra of unprecedented quality are contained in the IRTF library. The compilation of IR spectra by Lançon & Mouhcine (2002) is particularly useful for upper-AGB stars. Using these new ingredients, Charlot & Bruzual (2010, CB10) have built a series of population synthesis models that overcome many of the problems present in previous generations of models, e.g. BC03.

The excess flux in the U band present in previous models for 10 Myr populations, found by several authors and reported by Walcher et al. (2008) when studying a large sample of galaxies (VVDS), is now understood as being due to a lack of intermediate effective temperature main sequence stars in the STELIB and MILES libraries. These stars were assigned the spectra of hotter stars, producing this excess flux. When these libraries are supplemented with the theoretical model atmospheres atlas mentioned above, a good match with the observations is obtained. The figure below, kindly produced by J. Walcher using the CB10 models, should be compared with the published version by Walcher et al. The inclusion in the population synthesis models of the Lanz & Hubeny model atmospheres for O and B type stars allows the computation of a realistic value for the number of HeII ionizing photons in young populations down to Z=0. The Westera et al. stellar atmospheres predict unrealistically low figures for this number. Synthesis models built with the HNGSL allow to study in detail the behavior in time of UV line strength indices. As indicated by Bruzual (2007), more realistic galaxy mass estimates are obtained for distant galaxies using the new TP-AGB evolutionary prescription.
Mapping the stellar populations of the Milky Way with Gaia
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Gaia is a cornerstone mission of the European Space Agency planned for launch in mid 2012, with an expected duration of 5 (+2) years. It will perform an all sky (i.e. ~ 40,000 deg$^2$) survey complete to $V = 20-22$ observing ~ one billion celestial objects, and providing micro-arcsec accuracy astrometry (parallaxes, positions, proper motions) and accurate optical spectrophotometry (luminosities, astrophysical parameters). Spectroscopy at $R=11,500$ on the Ca Triplet (radial velocities, rotation, chemistry) will also be obtained to $V = 16-17$. This will allow to obtain a 5D (some 6D … up to 9D) phase space survey of the stellar populations in the Milky Way.

The primary objective of Gaia is the Galaxy: to observe the physical characteristics, kinematics and distribution of stars over a large fraction of its volume, with the goal of achieving a full understanding of its dynamics and structure, and consequently its formation and history.

In particular, some examples will be illustrated of how Gaia will map the physical characteristics and dynamical structure of the MW bulge, disk and halo, its impact on specific objects such as open and globular clusters, and its fundamental contribution to the trigonometric calibration of primary distance indicators leading to a definitive and robust definition of the cosmic distance scale.

Comparable astrometric accuracy can be obtained from some present and future space- or ground-based facilities, but on small areas of the sky.

Examples of how Gaia will observe typical halo populations as a function of distance. The globular cluster CMDs are from Piotto et al. 2002, A&A, 391, 945.
Current Uncertainties in Stellar Evolution Models

Santi Cassisi

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Abstract:

During this last decade our knowledge of the evolutionary properties of stars has significantly improved. This result has been achieved thanks to our improved understanding of the physical behavior of stellar matter in the thermal regimes characteristic of the different stellar mass ranges and/or evolutionary stages. This notwithstanding, the current generation of stellar models is still affected by several, not negligible, uncertainties related to our poor knowledge of some thermodynamical processes and nuclear reaction rates, as well as the efficiency of mixing processes. These drawbacks have to be properly taken into account when comparing theory with observations, to derive evolutionary properties of both resolved and unresolved stellar populations. We review the major sources of uncertainty along the main evolutionary stages, and emphasize their impact on the studies of both resolved and unresolved stellar populations. We show also how recent, accurate observational data represent fundamental benchmarks for stellar models.
Most stars form in clusters, rather than in the (unclustered) field regions of galaxies. This means that most stars that we observe in galaxies have, at some point, lived in a star cluster.

The primary window into the formation and evolution of star clusters comes from their mass ($M$) and age ($\tau$) distributions. We have analyzed clusters in the LMC, SMC, M83, and the Antennae, and find that the joint distribution of cluster masses and ages for clusters younger than $\sim 10^9$ yr can be described, to first order as:

$$g(M,\tau) \propto M^\beta \tau^\gamma$$

with $\beta \sim -2$ and $\gamma \sim -1$.

The cluster mass functions are approximately independent of age, and cluster age distributions are approximately independent of mass (see figure). A compilation of results from the literature suggests that this formula may describe the young cluster populations in more than a dozen galaxies, including dwarf and giant galaxies, isolated and interacting galaxies, irregular and spiral galaxies. We suggest that this “universal” shape for $g(M,\tau)$ is due primarily to similar disruption rather than formation histories for the clusters. Our results are discussed fully in Whitmore et al. 2007 (AJ, 133, 3606), Fall et al. 2009 (ApJ, 704, 453), Chandar et al. 2010a (ApJ, 711, 1263), and Chandar et al. 2010b (ApJ, 713, 1343).
**Stellar Populations in the Cosmological Context**  
STScl May Symposium (2010)

**Metallicity Gradients and Milky Way Disk as Observed by the SEGUE Survey**  
Judy Cheng, Constance Rockosi (UC Santa Cruz)

**Abstract:** Observations of old stars in the Milky Way's disk are ideal for providing detailed constraints on models of disk formation and evolution. Both secular processes and mechanisms within a cosmological context – such as mergers and accretion – may have important effects on disk growth at early times. Thus, the observed kinematics, spatial distribution, and compositions of old disk stars in the galaxy can serve as a testbed for models of disk formation and serve as a complement to studies of disks at high redshift. We study the radial and vertical metallicity distribution of the Milky Way disk using medium resolution spectra of 7712 main sequence turnoff stars from the Sloan Extension for Galactic Understand and Exploration (SEGUE). The sample consists of mostly old (> 8 Gyr) thin and thick disk stars, with a minimal contribution from the stellar halo. We present the radial metallicity gradient as a function of vertical height above the disk in the region \(6 < r < 16 \text{ kpc}, 0 < |z| < 1.5 \text{ kpc}\). The radial gradient becomes shallower as the distance from the galactic plane increases. We compare these results with previous radial metallicity gradient results from studies of open clusters. Because various mechanisms affect the metallicity distribution in the disk, these data may be used to distinguish between different formation models.

**Motivation:**

- The observed negative radial metallicity gradient of the thin disk suggests that it experienced a quiescent inside-out formation
- Similarly, the presence or lack of a gradient in the thick disk can provide clues about its formation – different formation scenarios make different predictions
- Thick disk stars are old – a good “fossil record” of the early formation of the galaxy

**Questions:**

- How do the radial metallicity gradients of the thin and thick disks compare?
- Is there a discontinuity in the gradient at large radii? (e.g., Yong et al. 2005)

**Results:**

- The gradient for low \(|z|\) agrees with previous work (e.g., Friel et al. 2002, Luck et al. 2006)
- The gradient becomes flatter at high \(|z|\)
- The flat gradient at high \(|z|\) is consistent with the “floor” seen in outer disk open clusters (Yong et al. 2005) – the increase in vertical height may contribute to the observed trend

**Left:** The radial metallicity gradient in four bins of vertical height \(|z|\). The mean metallicity corrected (uncorrected) for the selection function is shown in red (blue). Data are shown in blue (SEGUE) and open symbols (open clusters). The numerical values of the slopes are indicated in each panel, with the slope of the raw data in parentheses. **Right:** The measured gradients as a function of \(|z|\), with the number of objects in each bin indicated.

The recent discoveries of multiple stellar populations in massive Milky Way globular clusters (GCs) have provided the evidence that Helium abundance anomalies are primordial in the GCs. In order to keep pace with these discoveries, we have constructed the Yonsei Evolutionary Population Synthesis (YEPS) model with Helium enhanced populations, based on the most up-to-date Y2 isochrones and HB evolutionary tracks. We present integrated spectro-photometric quantities of Helium enhanced populations with special care in dealing with the morphologies of horizontal branch stars (HBs) with respect to metallicity, age, and Helium contents. Our new model provides completely new insight not only on the UV upturns of early type galaxies but also on the unexpectedly strong Balmer-lines of local early type galaxies.
Pre-Main sequence Turn-On as a chronometer for young clusters: NGC346 as a benchmark

Michele Cignoni (INAF - Astronomical Observatory of BOLOGNA, Italy)

Co-authors: M. Tosi, E. Sabbi, A. Nota, S. Degl'Innocenti, P.G. Prada Moroni, J. S. Gallagher

The main sequence (MS) turn-off is the most reliable feature for age-dating a star cluster. Nevertheless for very young clusters, with ages of tenths to few Myr, the identification of the turn-off is usually hampered by the paucity of massive stars. We propose to take a different point of view, focusing on the Turn-On (TOn), the CMD locus where the pre-main sequence (PMS) joins the MS. In the MS luminosity function of the cluster, the TOn is identified as a peak followed by a dip. We propose that by combining the CMD analysis with the monitoring of the spatial distribution of MS stars it is possible to reliably identify the TOn in star forming regions. Compared to alternative methods, this technique is complementary to the turn-off dating and avoids the systematic biases affecting the PMS phase. We describe the method and its uncertainties, and apply it to the star forming region NGC346, which has been extensively imaged with the Hubble Space Telescope.

Figure: The top-left panel shows the CMD selection of bona-fide main sequence stars (black dots). Each of the other panels shows the spatial distribution of these MS stars for the labeled range of magnitudes.

Hydrodynamical simulations can now produce large scale complexes of star clusters, containing many thousands of stars, whose clustering properties (e.g. the cluster shapes, mass functions, IMFs, degree of mass segregation and virial ratios) offer an excellent opportunity for comparison with surveys of embedded star forming regions. I report on the analysis of an observer’s view of the largest such simulation to date (1,2), and elaborate how stars in various regions of the IMF acquire their mass as they undergo the process of hierarchical merging into successively richer clusters.

**NEW RESULT - HIGH MASS STAR FORMATION VIA STELLAR COLLISIONS IN POPULOUS CLUSTERS?** Recent Nbody calculations (Moeckel et al in prep.) support our result from Monte Carlo simulations (3), i.e. that accretion induced collisions are a probable source of massive stars in the cores of high N clusters.

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**Stellar Populations in the Cosmological Context**  
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**Z-PAndAS – A spectroscopic survey of Andromeda**

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Co-authors: Scott Chapman, Mike Irwin, Rodrigo Ibata, Mike Rich, Annette Ferguson, Alan McConnachie, Nicolas Martin, Jorge Penarrubia, Dan Zucker and the PAndAS collaboration

The Z-PAndAS spectroscopic survey of M31 began in 2005, using the DEIMOS instrument on the Keck II telescope, to compliment the photometric PAndAS survey (McConnachie et al., 2009), using MegaCam on the CFHT telescope. To date, we have surveyed over 75 fields, containing >16000 Red Giant Branch stars. Our survey has probed the entire extent of M31, focusing on the disc and halo regions. Results from this survey have established the existence of an extended thin stellar disc that exists out to > 40 kpc (Ibata et al. 2005), the presence of a smooth, underlying halo structure (Chapman et al. 2006), characterized the properties of several unusual satellites (Chapman et al. 2007, Collins et al. 2009, LeTarte et al. 2009, Collins et al. 2010a, Collins et al. 2010b, in prep), as well as a number of tangential streams (Chapman et al. 2008) and a hot, thick disc component that lags the thin stellar disc of M31 and is more metal poor than the thin disc (Collins et al. 2010c in prep). Our survey of a number of faint dSphs has shown that these objects are colder and inhabit less dense dark matter halos than their Milky Way counterparts (Collins et al 2010a), however in terms of their metallicities they are very similar. We now possess data for additional M31 dSphs that will allow us to further study these unexpected differences and similarities, and shed some light on these smallest of galaxies.

**Left:** Top left – rh vs. oν for the MW (green triangles, Walker et al., 2009), And IX, XI, XII and XIII (red squares, Collins et al., 2010a), and other M31 dSphs (blue triangles, Kalirai et al., 2010). We overplot the Walker mass profiles, and it can be seen that a number of M31 dSphs appear cooler than their MW counterparts. Top right – Mv vs. oν for the MW and M31 dSphs., with the M31 dSphs again appearing cooler than their counterparts. Bottom left – rh vs. Mhalf. The colder dispersions of these objects translate into lower masses for the M31 dSphs and also - bottom right – lower central densities, suggesting significant differences in the dark matter halos of these objects.

**Right:** Co added spectra for the thin disc and thick populations as selected with our 2σ (top panel) and Gaussian fit (lower panel) criteria. In both cases, the thick population is found to be more metal poor by ~0.2 dex.

We present the first detailed chemical abundances of globular clusters (GCs) in M31, the dwarf irregular NGC 6822, the dwarf elliptical NGC 205, and the LMC. We have obtained these from high resolution spectra of their integrated light (IL) and using a new analysis method developed with a Milky Way (MW) and LMC GC “training set.” We measure individual absorption features to obtain detailed abundances for over 20 α−, Fe-peak, and neutron-capture elements. We also obtain age and stellar population constraints. These are the first detailed abundances for old stellar populations in normal galaxies beyond the Milky Way and are therefore the most detailed constraints to date on the formation and enrichment history of galaxies beyond our own.

Results:
- GCs in the MW, M31, and NGC 205 have higher [Ca/Fe] and [Si/Fe] than GCs in the LMC and NGC 6822
- LMC GCs show decreasing [Ca/Fe] with age, and systematically high [Mn/Fe]
- Young GCs in the LMC and NGC 6822 have high [Ba/Fe]
- Low resolution [Fe/H] measurements generally agree within the uncertainties.
- [α/Fe] from low resolution measurements are systematically lower, possibly due to the effect of GC star-to-star abundance variations on Mg absorption features

See Colucci et al. (2009, 2010), McWilliam & Bernstein (2008), and Cameron (2009)

Figure 1. Abundance ratios. Left panels include the abundances for our MW training set IL spectra, initial M31 GC sample, and NGC 205 GCs, shown by gray, green, and purple squares, respectively. Right panels include the abundances for our LMC training set IL spectra, and NGC 6822 GCs, shown by red and blue squares, respectively. Small gray points show MW abundances from individual stars (from Venn et al. 2004, Pritzl et al 2005, and references therein). Small red points show LMC abundances from individual stars (Pompeia et al 2008, Johnson et al. 2006) and small blue points show abundances for young stars in NGC 6822 (Venn et al. 2001).
Stellar Populations in the Cosmological Context
STScI May Symposium (2010)

Stellar Population Synthesis: Which Uncertainties Matter?
Charlie Conroy (Princeton)

Collaborators: Jim Gunn, Martin White, David Schiminovich, Michael Blanton

While great progress has been made in the construction of reliable SPS models in the past
decade, serious uncertainties remain in each of the major SPS ingredients, including
advanced stellar evolutionary phases, dust attenuation, the IMF, and the spectral libraries. I
will discuss ongoing work on two fronts that aims to understand and constrain these uncertain
aspects: 1) constraining the TP-AGB phase using both LMC star clusters and post-starburst
galaxies; 2) estimating average UV through near-IR dust attenuation curves in low-redshift
star-forming galaxies. Results from these studies demonstrate that significant uncertainties
remain, especially in the near-IR and near-UV. However, we emphasize that it is possible to
jointly constrain both the uncertain SPS ingredients and the physical properties of galaxies.

Colors of 'super starclusters', constructed by stacking
many LMC clusters in age bins, compared to SPS model
predictions (from the FSPS code of Conroy et al. 2009).
Two models are shown where the only difference is in
the treatment of the TP-AGB evolutionary phase. In one
all cases the unmodified Padova isochrones are used. In
the other, the isochrones have been modified to fit the
LMC data. State-of-the-art TP-AGB models produce
near-IR colors too red compared to observations.

Average SEDs of face-on and edge-on disk-dominated
star forming galaxies at z<0.05. The strong dust
feature at 2175Å is clearly visible in the edge-on
sample. This is the first detection of this feature in the
average attenuation curve of low redshift star forming
galaxies and implies that use of standard dust
attenuation curves (such as the Calzetti et al. curve for
starbursts or a power-law curve) will significantly
underestimate the attenuation around 2175Å.

References:
A Multi-Color Optical Survey of the Orion Nebula Cluster. The New H-R Diagram

Nicola Da Rio (Max Planck Institute for Astronomy)


The Orion Nebula Cluster (ONC) is the closest site of active massive formation, and therefore regarded as a prototype of dense star forming regions. We present a new analysis of the ONC stellar population, based on the most complete and accurate set of optical photometric data in this region (Da Rio et al. 2009). Based on multi-band, simultaneous, optical photometry as well as new spectroscopy and spectra from the literature, we are able to accurately place ~1000 members in the H-R diagram. We find evidences that the intrinsic colors of ONC members differ from those of MS-dwarfs, while are in agreement with synthetic photometry results utilizing state of the art atmosphere models; we develop a method to accurately disentangle color excesses due to mass accretion and dust extinction. We determine an average age for the ONC higher than previous works (e.g. Hillenbrand 1997), peaking at 2-3Myr with no evidence for mass-age correlations. We determine the IMF complete down to the H-burning limit, and find that it peaks and presents a turn-over at M~0.2Msun, while for intermediate masses we confirm a Salpeter slope.

Left: H-R diagram of the ONC, with PMS tracks and isochrones from Siess et al (2000) and Palla & Stahler (1999)
Middle: Density distribution of the ONC members in the mass-age plane, according to Siess (2000) and Palla & Stahler (1999) evolutionary models. Numbers are corrected for detection incompleteness and selection of the sample of members with available effective temperature.

A maximum-likelihood approach to constrain ages and age spreads in young clusters

Nicola Da Rio (Max Planck Institute for Astronomy)

Co-authors: D. A. Gouliermis, M. Gennaro

An open question in the observational study of young stellar systems concerns the problems related to age estimation. In case of photometric data, the disagreement between different theoretical evolutionary models, together with the observational and physical uncertainties, make an accurate determination of ages and possible age spreads rather challenging. We present a maximum-likelihood method in the CMD to assign ages to PMS cluster members accounting simultaneously for photometric errors, unresolved binarity, source confusion, CTTS variability, differential reddening. The concept is to fit the data not with a 1D isochrone, but with a 2D distribution in the CMD that represents the probability, for a star of a given age, to be detected in each point of the CMD. This method allows us to derive an unbiased estimate of the cluster age. Furthermore, the analysis of the goodness-of-fit allows us to accurately disentangle the apparent spread in the CMD typically seen in PMS systems and the real age spread.

We apply the method to the stellar association LH95 in the LMC, observed with HST/ACS down to 0.2 solar masses (Gouliermis et al. 2007; Da Rio et al. 2009). We find that: A) The age of LH95, (6.2-7.5Myr) is 25-50% higher than what derived with a simple isochrone fit. B) We disentangle the real age spread from the apparent broadening of the observed sequence. The true age distribution has a standard deviation of 4Myr. C) We find a correlation between average age with luminosity, which suggests an inaccuracy of the theoretical evolutionary models.

Left: Observed CMD of LH 95. The blue line indicates a 2Myr Siess (2000) isochrone, while the orange area indicates the same isochrone, after the application of binarity, variability, crowding, and differential extinction; the color is proportional to the square root of the probability, for a star 2Myr old following the Siess interior models, to be measured in a given point of the CMD.

Right: Likelihood functions for the entire stellar sample, as a function of age. These functions indicate a probability, for the observed sequence, to be compatible with a model isochrone accounting binarity, variability, differential extinction, crowding and photometric errors. Results are obtained assuming both FRANEC (Tognelli et al 2009) and Siess (2000) evolutionary models, and several binary fractions f.

Galaxies as Collections of Individual Stars

Julianne Dalcanton (University of Washington)

Co-authors: Ben F. Williams, Jason Melbourne, Leo Girardi, Dan Weisz, Evan Skillman, Karrie Gilbert, Andy Dolphin, & the ANGST collaboration

The optical and infrared colors and luminosities of a galaxy depend sensitively on the exact mixture of its constituent stars. Unfortunately, broad-band integrated photometry and luminosity-weighted spectra provide only coarse indicators of the age and metallicity of the underlying stellar population. In nearby galaxies, however, we can dissect galaxies into their individual stars, and directly assess the contribution of different populations to the integrated light. I will discuss two large programs which harness the power of HST to resolve individual stars in large volume-limited samples of nearby galaxies. I will focus on the short-lived but luminous phases of stellar evolution that are revealed in optical and NIR color magnitude diagrams, and which can potentially contribute significantly to a galaxy's spectral energy distribution. I will highlight existing discrepancies and recent improvements to the modeling of AGB stars and core Helium burning stars, and show how these may propagate into NIR observations. I will also present an example showing how observations of individual stars can be used to trace fossil records from the epoch of peak star formation density.
The where, when, why and how of star formation in the Local Group*

Guido De Marchi (ESA),

N. Panagia (STScI), M. Romaniello (ESO), G. Beccari (ESA), L. Spezzi (ESA),
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Summary

We have undertaken a systematic study of pre main sequence (PMS) stars spanning a wide range of masses (0.5 – 4 M☉), metallicities (0.1 – 1 Z☉) and ages (0.5 – 30 Myr). We have used new WFC3 and archival ACS and WFPC2 observations to identify and characterise a large sample of PMS objects in three star forming regions in the local group, namely NGC 3603 in the Milky Way, 30 Doradus in the Large Magellanic Cloud and NGC 346 in the Small Magellanic Cloud. Thanks to a novel method that we have developed to combine broad-band (V; I) photometry with narrow-band Hα imaging, we have determined the physical parameters (temperature, luminosity, age, mass and mass accretion rate) of more than 2000 bona-fide PMS stars still undergoing active mass accretion (Figure 1). This is presently the largest and most homogeneous sample of PMS objects with known physical properties. The most important results of this research include:

- All regions exhibit multiple recent episodes of star formation with at least two populations of younger and older PMS stars separated by about 10 Myr from each other, suggesting a multi-generation pattern (Figure 2).
- There is no correlation between the projected spatial distribution of young and old PMS stars and the younger population is systematically more concentrated, contrary to what one could expect in a triggered star formation scenario (Figure 3).
- There is no correspondence between the positions of young PMS stars and those of massive OB stars of similar age, indicating that the conditions necessary for high- and low-mass star formations are most likely different (Figure 4).
- The mass distribution of stars with similar ages reveals variations throughout the regions, suggesting that the concept of initial mass function is not meaningful over the scale of a few pc that is typical of individual star-forming groups (Figure 5).
- The mass accretion rate appears to scale with the first power of the stellar mass, with the square root of the age, and approximately with the inverse of metallicity (Figure 6).
- There are signs of photo-evaporation of circumstellar discs caused by neighbouring younger massive stars (Figure 7). These results are bound to have important consequences on, and set firm constraints for our understanding of the star formation process.

* This work is partly based on ERS data made by the WFC3 Scientific Oversight Committee. We are grateful to the Director of the Space Telescope Science Institute for awarding Director’s Discretionary time for this programme.
Stellar Populations in the Cosmological Context
STScI May Symposium (2010)

Stars formed within HI debris of interacting galaxies

Duilia de Mello (CUA/GSFC)

Co-authors: Claudia Mendes de Oliveira, Fernanda Urrutia-Viscarra, Sergio Torres-Flores, Elysse Voyer, Linda Smith, Jay Gallagher, Gladys Vieira Kober

We present an overview of our study searching for star formation within HI debris using a variety of diagnostics. Our sample contains 34 galaxies that are going through collisions and have extended HI gas and GALEX data. We have identified dozens of stellar clusters candidates which are located outside the galaxies but within the HI debris. Our follow up data, which includes VATT, WIYN and Gemini data, reveal their masses, metallicities and SFR for a subsample of these objects. We have also searched the HST archive and found a few stellar associations, nicknamed blue blobs. Our results so far show that some of these young stellar populations were formed “in situ” from reprocessed gas which was ejected during the interaction. We are aiming at quantifying the amount of star formation that takes places in this type of environment which might be very common at high redshifts, when interactions were frequent and galaxies were gas rich, and might explain how the intergalactic medium got enriched at an early epoch.

Top left: Example of galaxy (NGC2782) with HI tidal debris in our sample. Top Right: Hα continuum subtracted image (VATT) showing regions in the HI tail. Bottom: Star-forming regions in the HI tail (GALEX+HI contour and Gemini r). NGC2782 (Arp 215) is at 34 Mpc.

**Stellar Populations in the Cosmological Context**  
*STScI May Symposium (2010)*

**The contribution of interacting binaries to the enrichment of globular clusters**

Selma de Mink (Astronomical Institute Utrecht)

Co-authors: Rob Izzard, Onno Pols and Norbert Langer

Various features in the color magnitude diagrams of globular clusters indicate the presence of multiple stellar populations within one cluster, differing in chemical composition and possibly age. It has been proposed that the more massive stars in the cluster enriched their surroundings with material processed by hydrogen burning. Two main sources have been suggested: asymptotic giant branch (AGB) stars and massive stars rotating near the break-up limit ("spin stars"). A challenge for all proposed scenarios is to provide the large amount of ejecta required to form subsequent stellar populations that are equally or even more numerous than the first population.

We propose massive binaries as a promising additional source of enrichment and we argue why this source might be more important than AGB stars and "spin stars", at least in terms of the amount of ejected mass. To demonstrate the principle we compute the evolution of a typical 20 solar mass star in a close binary considering the effects of mass transfer, rotation and tidal interaction. We find that this system sheds about 10 solar masses of material, about 5 times than in the "spin star"-scenario. This material is probably ejected at low velocity. We expect that it remains inside the potential well of the cluster and becomes available for the formation or pollution of a second stellar generation.

Given the high fraction of close binaries among massive stars in nearby loose OB associations, a fraction which may be even higher in the dense center of the young progenitor of massive globular clusters, it is likely that the majority of massive stars interact with a companion and contribute to the self-enrichment of the cluster. This scenario relieves the need to adopt commonly made assumptions such as strong preferential loss of the first generation of stars form the cluster, a very high fraction of fast rotating stars among massive stars, external pollution or an anomalous initial mass function.

**Figure:** Schematic representation **Left:** A binary system at the onset of mass transfer. The deepest layers in the donor star have been processed. The accreting star is spun up. **Right:** The companion star accreted just a fraction of the transferred mass, mainly unprocessed material originating from the outermost layers of the donor star. Material originating from deeper layers in the donor star is shedded into from the system.

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Stellar Evolutionary Implications of Individual Abundance Variations for -3 < [Fe/H] < 0

Aaron Dotter (UVic)
Co-authors: Don VandenBerg, Peter Bergbusch, and Jason Ferguson

Stellar models provide a framework for interpreting observations of resolved and unresolved stellar populations. These models typically assume a heavy element distribution based on the Sun or, for metal-poor stellar populations, an alpha-enhanced mixture. Spectroscopic studies indicate that detailed abundances vary as a function of [Fe/H] and the environment in which stars form. It is crucial to understand the influence of individual heavy elements on stellar evolution but, to date, theoretical studies have only scratched the surface. Preliminary results are presented from an effort to examine the effect of individually varying the abundances of C, N, O, Ne, Na, Mg, Si, S, Ca, and Ti at fixed [Fe/H] from -3 to 0 and Y=0.25, 0.29, and 0.33. We demonstrate the influence of the most significant elements, O, Mg, and Si, and compare them with models assuming scaled-Solar and alpha-enhanced abundances.

Caption: Isochrones with [Fe/H]=-1.4 at 12 Gyr. AGS05 is the Asplund et al. (2005, ARAA, 43, 481) Solar abundances. AGSC adds 0.3-0.5 dex enhancements of O, Ne, Mg, Si, S, Ca, and Ti to AGS05. AGSC+X adds an additional 0.4 dex of element X. Left shows isochrones in the H-R diagram; right compares them with M5 (Stetson, 2000, PASP, 112, 925). O effects the MSTO (MS lifetime) but not appreciably the RGB. Mg and Si make the RGB substantially cooler without significantly altering the MSTO.
30 Doradus: The Quintessential Resolved “Starburst”

Chris Evans (UK Astronomy Technology Centre, Edinburgh)

30 Doradus in the Large Magellanic Cloud provides us with an essential bridge between studies of spatially-resolved star formation/cluster evolution, and the intense starburst clumps seen at high redshift. In summarising recent results, I will focus on multi-epoch spectroscopy of the luminous WN stars at the core of R136 (Schnurr et al., 2009; five from six stars apparently single), O-type stars across the wider cluster (Bosch et al., 2009; 50 stars observed, with binary fraction of ~50%), and the on-going VLT-FLAMES Tarantula Survey (Evans et al., 2010; >300 O-type stars observed). Constraining the binary fraction has tremendous importance for our models of both star formation and stellar evolution models. The power of the new VLT survey will be illustrated by observations of a very massive runaway star on the outskirts of 30 Dor, for which HST-COS spectroscopy reveals one of the highest terminal wind velocities known.

New facilities and new techniques are also giving us ever better views of this beautiful cluster, e.g. HST-WFC3, and wide-field, adaptive optics (AO) corrected imaging from VLT-MAD (Campbell et al., 2010; Fig. below). The MAD observations employed multi-conjugate AO – a key technique for the future Extremely Large Telescopes (ELTs) which, in combination with JWST, will truly herald a new era of observational astronomy.

![Image](central_1x1_of_the_H-_K-band_VLT-MAD_mosaic_of_R136_Campbell_et_al_.2010.jpg)

**Fig:** Central 1' x 1' of the H- & K-band VLT-MAD mosaic of R136 (Campbell et al., 2010).

A Ghost and its Host: M31's Giant Stream Debris

Mark Fardal (University of Massachusetts)

Collaborators: Martin Weinberg, Arif Babul, INT team (Mike Irwin, Rodrigo Ibata, Annette Ferguson, Alan McConnachie, Geraint Lewis, Nial Tanvir), SPLASH team (Raja Guhathakurta, Karrie Gilbert, Jason Kalirai, Mikito Tanaka, Masashi Chiba, Evan Kirby, Erik Tollerud)

A giant stream of metal-rich stars extends 150 kpc into M31's southern halo (the Giant Southern Stream or GSS, Ibata01; see M31 talks at this meeting). Many other other tidal features surround M31, and two, the NE and W shelves, have stellar populations quite similar to the giant stream (Ferguson02, Richardson08). We previously showed our dynamical models of a satellite galaxy colliding with M31 (Fardal07) agree well with the morphology and kinematics of these tidal features. In principle our model can help separate GSS from unrelated debris around M31, specify the nature of the original satellite, and measure the strength of M31's potential. But how confident are we that our specific trajectory is correct? And how precise are the constraints on the parameters in this model?

Figure 1 (left) shows stellar velocities observed recently in the W shelf by the SPLASH collaboration, which our model describes as the third radial wrap of GSS debris since disruption of the progenitor. Red diamonds show stars classified from their photometry, spectra, and velocities as M31 stars, cyan those classified as Galactic. The model points (small dots) include the GSS debris that forms the shelf (magenta) as well as a hot smooth halo (green). The agreement of the data with the predicted "wedge" kinematic pattern is striking. The metallicity distribution of shelf stars as selected via their kinematics differs from the broader halo component, but agrees well with that of the GSS itself. These observations thus show strong support for our model.

Constraining the parameters in the model is not easy, since the detailed morphology cannot be predicted analytically. We have developed a technique for sampling parameter space using N-body models coupled to MCMC. The likelihood function incorporates the surface density pattern of the debris based on the INT star-count maps, as well as velocity and distance measurements within the GSS. This technique yields the probability distribution of parameters including the orbital trajectory of the satellite, its original mass, and the halo mass of M31. Figure 2 (right) shows the joint distribution of M31 halo mass and GSS progenitor mass. The halo mass is consistent with the timing argument (Li08).

A picture emerges of a satellite comparable in mass to the LMC, quite recently deceased. However, the stellar population is very different from the LMC, since most stars are ~8 Gyr old and none are younger than 4 Gyr (Brown06). The satellite's disruption time of ~700 Myr ago is much smaller than these typical ages, suggesting gas stripping at earlier times. This work shows how the cooperation of resolved stellar population observations and dynamical models helps to decode the complex patterns and mass distribution in a galaxy's halo.
The Calcium Triplet as a Metallicity Indicator for Unresolved Stellar Populations: a new puzzle? (based on Foster et al. 2010a, AJ, 139, 1566)

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The Calcium Triplet (CaT) has been employed as a metallicity indicator for resolved Galactic and Local Group stars as well as for the integrated light of Milky Way globular clusters (GCs) and galaxies. Single stellar population models predict that the CaT should be an adequate metallicity indicator (Bruzual & Charlot 2003, MNRAS, 344, 1000; Vazdekis et al. 2003, MNRAS, 340, 1317). On the other hand, its usefulness in determining metallicities for the “simplest” unresolved systems, i.e. extragalactic GCs, has not been tested.

Using DEIMOS on Keck we obtain spectra of 144 GCs around NGC 1407 to test whether or not the CaT can be used as a metallicity indicator for extragalactic GCs. We use the empirical conversion of Armandroff & Zinn (1988, AJ, 96, 92) based on Milky Way GCs to convert CaT to metallicity. The measured CaT/metallicity distributions show unexpected features, the most puzzling being that the brightest blue and red GCs have similar CaT depths (see Figure 1) suggesting they have a similar metallicity ([Fe/H]~ 0.8 dex) despite their large difference in mean color. This is not seen among Milky Way GCs. Possible explanations for this behavior are 1) the presence of hot blue stars artificially inflating the CaT index values, 2) color does not trace metallicity as expected, or 3) the CaT index saturates at lower metallicity than predicted by the Vazdekis et al. (2003) single stellar population models. Based on recent results from the galaxy NGC 4494 (Foster et al. 2010b, in prep.) we argue that the former of these is most likely.

Figure 1 (left): Average spectrum for the brightest blue and red GCs around NGC 1407.

Figure 2 (right): The CaT inferred metallicity magnitude diagram. Red and blue symbols and lines correspond to the red and blue GC subpopulations, respectively. Solid lines show rolling averages.
We present the first method to estimate properties of unresolved stellar clusters which explicitly takes into account the discrete properties of the IMF. The method we developed is a Bayesian approach which provides posterior probability distributions in particular in the age-mass-extinction space, using multi-wavelength photometric observations and a large collection of Monte-Carlo simulations of synthetic clusters with finite stellar masses. Through this approach, we also exhibit and explain systematics arising from the use of classical estimation method based on continuous population synthesis models, which by definition suppose fully populated IMFs, in other words, an infinite mass for the studied populations. Systematic errors on age and mass estimates are large especially for relatively small clusters: a few $10^5$ Msun and smaller. Systematic errors are significantly smaller with the Bayesian method. Taking stochasticity into account is important, more important for instance than including near-IR data in many cases.

Resulting estimates based on U, B, V, I and K band, allowing any extinction $A_v$ between 0 and 3. On the left-hand side, the age estimations. On the right-hand side, the mass estimations. Estimations from the Bayesian approach are given in the two upper panels and standard estimates considering continuously populated IMF are given in the two lower panels. The x-axes represent, respectively, the original age and mass of the sampled populations whereas the y-axes represent the estimated values from the two methods. Dashed lines highlight the identity function. Open circles highlight poor fits where the reduced chi$^2$-values exceed 1 by more than 3 standard deviation of the adequate chi$^2$-law.

More details can be found in Fouesneau, M., & Lançon, A. 2010, arXiv:1003.2334
Dwarf elliptical (dE) galaxies are the dominant galaxy type by number in nearby galaxy clusters. Understanding the formation and evolution of the dE galaxy class will provide insight into dwarf galaxy evolution and the assembly of dense environments. We present deep ACS and WFC3 imaging for the Local Group dEs NGC 147 and NGC 185. These are the only two dE galaxies in which HST can cleanly resolve stars below the main sequence turnoff and thus directly measure their star formation histories. In combination with ground-based kinematic and abundance measurements, these observations are a unique opportunity to test formation models for an entire galaxy class.

**FIGURE 1:** Image of NGC 147 showing the position of HST WFPC2, and deep ACS and WFC3 pointings. The orange symbols indicate Keck/DEIMOS spectroscopy of individual stars in NGC 147.

**FIGURE 2:** Preliminary ACS CMD of NGC 147 reaching below the main sequence turnoff. An old, metal-poor isochrone is shown for comparison.
Globular cluster systems in most large galaxies display bimodal color and metallicity distributions, which are often interpreted as indicating two distinct modes of cluster formation. The metal-rich and metal-poor clusters have systematically different locations and kinematics in their host galaxies. However, the red and blue clusters have similar internal properties, such as the masses, sizes, and ages. It is therefore interesting to explore whether both metal-rich and metal-poor clusters could form by a common mechanism and still be consistent with the bimodal distribution. We present such a model, which prescribes the formation of globular clusters semi-analytically using galaxy assembly history from cosmological simulations coupled with observed scaling relations for the amount and metallicity of cold gas available for star formation. We assume that massive star clusters form during mergers of massive gas-rich galaxies and tune the model parameters to reproduce the observed distribution in the Galaxy. A wide, but not entire, range of model realizations produces metallicity distributions consistent with the data. We find that early mergers of smaller hosts create exclusively blue clusters, whereas subsequent mergers of more massive galaxies create both red and blue clusters. Thus bimodality arises naturally as the result of small number of late massive merger events. This conclusion is not significantly affected by the large uncertainties in our knowledge of the stellar mass and cold gas mass in high-redshift galaxies. The fraction of galactic stellar mass locked in globular clusters declines from over 10% at $z>3$ to 0.1% at present.

On The Nature Of Multiple Stellar Populations In Star Clusters In The Magellanic Clouds (And Elsewhere?)

Paul Goudfrooij (STScI)

Co-authors: Thomas Puzia (HIA), Vera Kozhurina-Platais (STScI), and Rupali Chandar (U. Toledo)

Abstract: We present deep HST/ACS color-magnitude diagrams of 6 intermediate-age (1-3 Gyr) star clusters in the Large Magellanic Cloud. We find evidence for a significant spread in color in the main sequence turnoff (MSTO) region in all target clusters. This spread is not caused by binary systems, measurement errors, or contamination by field stars. Using isochrone fits and simulations, we suggest that the most likely cause of the color spread is a range of ages of 200-500 Myr for the cluster stars. We find that stars in the upper (younger) part of the MSTO region are often more centrally concentrated than (i) stars in the lower (older) part of the MSTO and (ii) stars in the RGB and AGB (which are more massive!).

Using model predictions of the evolution of masses and half-mass radii during the cluster’s lifetime, we find evidence for a relation between the relative level of central concentration of the younger vs. the older halves of the MSTO region and the escape velocity at cluster birth (see Fig. 1 below). The latter is estimated to be of order 10-20 km/s, large enough to retain material lost by slow winds of massive rotating stars or intermediate-mass AGB stars of the initial stellar population. We suggest that the presence of secondary stellar populations in these star clusters is caused by processes internal to the clusters rather than accretion or trapping of external material. Such a scenario could also naturally explain the light-element variations observed among stars in most ancient Galactic globular clusters.

The figure on the left shows the ratio of the radial profiles of stars in the upper vs. the lower MSTO region, plotted against the calculated escape velocity of the star clusters at the tidal radius at birth. Note that the younger generation of stars is more centrally peaked for star clusters with higher initial escape velocities.

(The calculation of the initial escape velocities involves mass estimates from SSP models, best-fit King models of the star density distributions, and integrated mass loss due to stellar evolution and two-body relaxation processes.)
Stellar Populations in the Cosmological Context!
STScI May Symposium (2010)

Mass-Dependent Star Formation, Stochastic Assembly-Driven Quenching

Genevieve Graves (UC Berkeley)

Co-authors: Sandra Faber, Ricardo Schiavon, Guinevere Kauffmann, & Gabriella DeLucia

To zeroth order, early type galaxies form a one-dimensional family in which their observed properties—color, metallicity, environment, central black hole masses—all scale with their mass. This makes it difficult to disentangle the critical properties that determine their evolutionary history because everything correlates with everything else. Examining where this 1D sequence breaks down can provide essential clues to galaxy evolution. I present observational evidence that galaxy star formation histories form a 2D family, such that galaxies of the same mass today start out with similar star formation histories but shut down star formation (“quench”) at different times. A parallel study using semi-analytic models of galaxy evolution suggests that these differences are due to their underlying halo mass assembly histories. Indeed, the observed 2D family of galaxy star formation histories seems to be a generic result of a mass-threshold for quenching, given a standard ΛCDM paradigm that includes mass-dependent evolution and stochastic hierarchical assembly.

Left: The 2D family of early type galaxy star formation histories. Higher-σ galaxies have older ages, and higher [Fe/H] (also higher [Mg/H] and higher [Mg/Fe], not shown) than those with lower σ. At fixed σ, galaxies with higher dynamical mass-to-light ratios ($M_{dyn}/L$) are older and have lower [Fe/H]. They also have lower [Mg/H], higher [Mg/Fe], lower effective surface brightness ($I_e$), lower stellar mass surface density ($Σ$) and lower stellar mass ($M_*$).

Right: The ensemble of variations in galaxy properties at fixed σ can be explained by a “premature truncation” model for galaxy star formation histories, as illustrated here. In this model, galaxies at a given σ all start forming stars at similar times but quench at different times. Galaxies that quench early have older single-burst ages and enhanced [Mg/Fe]. Because they convert fewer of their baryons into stars, they also have lower metallicities (lower [Fe/H] and [Mg/H]), lower $Σ$, lower $M_*$, and lower $I_e$.

Semi-analytic models (SAMs) of galaxy formation and evolution based on the Millennium run reproduce many of the key features of this premature truncation model without any need for fine tuning. This suggests that these trends are a generic prediction of hierarchical assembly combined with a mass threshold for quenching star formation.

Graves et al. (2010, submitted) and Graves & Faber (2010, submitted)
Luminosity Functions and Photometric Properties of Ly-alpha Emitters from 2 < z < 3

Caryl Gronwall (Pennsylvania State University)

Co-authors: Eric Gawier, Lucia Guaita, Robin Ciardullo, John Feldmeier, Nicholas Bond, Harold Francke, Nelson Padilla, Ana Matkovic, Viviana Acquaviva, Jean Walker, Michael Berry, Christopher Wolf & the MUSYC Collaboration

We have used the Mosaic camera of the CTIO 4-m telescope to conduct deep, narrow-band surveys of Ly-alpha Emitting Galaxies (LAEs) in the Extended Chandra Deep Field-South over the redshift ranges 3.08 < z < 3.15 and 2.04 < z < 2.08. Our survey covers 0.28 square degrees down to a limiting line flux of about 1.5E-17 ergs/cm2/s at z=3.1. Our LAE sample now consists of several hundred candidate line-emitters. By combining our narrow-band data with archival broadband photometry from MUSYC (the Multiwavelength Survey by Yale-Chile), we have been able to determine the photometric properties of these samples. We will present results including the Ly-alpha and rest frame-UV luminosity functions of both redshifts, and discuss the evolution of this population of galaxies "in the act of formation." We will also discuss the equivalent widths, colors, star-formation rates, and dust properties of these objects.

Left: The observed evolution in the Ly-alpha emitter luminosity function from z=3 to 6 showing results from our z=3.1 survey (Gronwall et al.) and from Ouchi et al. There appears to be little evolution in the observed LAE LF from z=3 to 6.

Right: Top panel shows the observed distribution of equivalent widths for all the Ly emission-line galaxies in our z=3.1 sample. The dotted line shows the apparent best-fit exponential for the distribution; the solid curve shows the exponential after correcting for the effects of photometric error and our narrow-band filter bandpass. The lower two panels divide the sample in half, and demonstrate that the exponential law does not change much with galaxy luminosity. Less than 10% of our LAEs have rest-frame EW > 240 Angstroms as would be expected for a top-heavy initial mass function.

We report the detection of color gradients in 6 massive (M>10^{10} M\odot) galaxies with low specific star formation rate (SSFR<10^{-11} yr^{-1}) at redshift z~2 in the HUDF. The rest-frame optical morphology of these galaxies is consistent with that of spheroidal systems, but their sizes are generally smaller than that of today's early-types[1]. HST/WFC3 images[2] show that the inner regions of these galaxies have redder rest UV--optical colors than their outer parts. The slopes of the color gradients have no dependence on redshift, M*, or SSFR of the galaxies, however, they depend on the SED-fitting derived dust extinctions of the galaxies. The slopes of the color gradients of these galaxies are generally steeper than that of local elliptical galaxies. SED-fitting with spatially resolved HST seven--bands photometry from ACS and WFC3 images (BVizYJH) in concentric shells across the light profile of each galaxy, shows, under a number of assumptions for the metallicity (Z) gradients, that the redder inner regions of the galaxies have slightly higher dust extinction (\Delta E(B-V)=0.05) than the bluer outer regions, implying that a mild dust gradient contributes to the observed color gradients. Because of the age-metallicity degeneracy, the derived slopes of age and SSFR gradients depend on the assumed Z gradients: (1) for the free Z or constant Z gradient, outer parts are ~0.5 Gyr younger and have ~0.5 dex higher SSFR than the inner regions; (2) for the Z gradient of local early-type galaxies, outer parts are as old as the inner region, but have slightly higher (~0.3 dex) SSFR; and (3) for the maximal-Z gradients (as predicted by the monolithic collapse), outer parts are ~0.2 Gyr older than the inner regions, but have same SSFR as the inner regions. We conclude that the derived age gradients with the local or maximal-Z gradients are qualitatively consistent with the gradients of today's early-types, while those with the free or constant Z gradients are not[3].

Top: (z-H) colors of the 6 galaxies (with GOODS V2.0 ID labeled). Magenta circles show the shells used to measure the color and stellar population gradients. Left: the rest-frame colors gradients (colors as a function of the times of H-band effective radius) of the galaxies. Middle: The slopes of the rest-frame color gradients as a function of the dust extinction of the galaxies, compared with the slopes of local early-type galaxies (dotted lines). Right: The dust, age, and SSFR gradients under various assumptions for the Z gradients. Black solid and dashed lines show the mean and 1\sigma of the slopes of gradients (with galaxy 24626 excluded).

• We define the “first stars” (aka “earliest stars”, “oldest stars”) as stars born within a few 100 million years after the big bang

• Theory suggests that most of the earliest stars are with us now – in the cores of luminous red galaxies

• The presence of the oldest stars in LRG’s should be detectable in the restframe mid-UV where they greatly outshine slightly younger, background stars of the same mass

• The Sloan Digital Sky Survey (SDSS) has observed tens of thousands of z>0.4 LRG’s in the restframe mid-UV

• First attempts to detect the earliest stars in z>0.4 LRG’s spectra are inconclusive due to calibration issues (systematic errors in the sky subtraction) with Sloan spectra

• An ELT should be able to make definitive observations of the first stars
Erik Hoversten (Penn State/Swift)

Co-authors: Caryl Gronwall, Dan Vanden Berk, & Pete Roming

We present Swift UV/Optical Telescope (UVOT) imaging of the galaxies M81 and Holmberg IX. We combine UVOT imaging in three near ultraviolet (NUV) filters (uvw2: 1928 Å, uvm2: 2246 Å, and uvw1: 2600 Å) with ground based optical imaging from the Sloan Digital Sky Survey to constrain the stellar populations of both galaxies. In agreement with earlier studies we find evidence for a burst in star formation in both galaxies starting ~200 Myr ago coincident with the suggested time of an M81-M82 interaction. In line with theories of its origin as a tidal dwarf we find that Holmberg IX is a very young galaxy. Both galaxies are best fit by a Milky Way dust extinction law with a prominent 2175 Å bump.

Top: False color images of M81 and Holmberg IX. At left is the UVOT ultraviolet image using the uvw1 (red), uvm2 (green), and uvw2 (blue) filters. At right is the SDSS optical image using the g (blue), r (green), and i (red) images.

Left: Histograms of the fitted parameters of individual star forming regions in M81 (thick line) and Holmberg IX (thin line). The derived parameters are the reduced chi-square (top left), age assuming a simple stellar population (top right), the V band extinction (bottom left), and the best fitting dust model (bottom right). Note that both galaxies prefer a dust law with a pronounced 2175 Å bump (MW, LMC) with none being best fit by the models without the bump (SMC, Calzetti starburst extinction).
A Study of M32’s Internal Kinematics: A Combination of Integrated Light and Resolved Star Spectroscopy

Kirsten Howley (UCSC)

Co-authors: Puragra Guhathakurta, Marla Geha, Jason Kalirai, Basilio Yniguez, Evan Kirby, Roeland van der Marel, Jean-Charles Cuillandre

We present new integrated light (\(r < 100''\)) and resolved star (\(100'' < r < 200''\)) spectroscopic observations of the galaxy M32 (\(r_{\text{eff}} = 28.5'' = 0.1\) kpc) using the DEIMOS instrument on the Keck II telescope. M32, a satellite of the Andromeda (M31) galaxy, is our nearest example of the rare and enigmatic compact elliptical galaxy type. It has long been known that the outer isophotes of M32 are distorted; this is presumed to be caused by its tidal interaction with M31. Previous kinematical studies of M32 have obtained a rotation curve and velocity dispersion profile out to \(r \sim 30''\) -- by contrast, our new measurements of M32’s stellar kinematics extend out to nearly \(r = 200''\), just beyond the tidal distortion radius of \(r \sim 150''\). Our kinematical study of the low surface brightness outlying region of M32 is made challenging by the fact that it is projected against the bright/complicated inner regions of M31. However, we use surface brightness and kinematical trends versus sky position to statistically account for contamination of this region by M31’s disk and bulge stars. Unlike NGC 205, another close neighbor of M31, M32's kinematics appear to be regular and symmetric and do not show obvious sharp gradients across the tidal distortion region. This lack of a strong gradient will serve as a constraint on tidal interaction models. At present, the velocity and dispersion profiles obtained from these data are being used to measure the mass profile of M32 through Jeans modeling.

Left: M32’s semi-major axis velocity and dispersion profiles from integrated light and resolved stellar spectroscopy.
Right: Five observed DEIMOS multi-slit masks and predicted fractional light contribution from M32. As a result of M32's close proximity to M31, the majority of the masks fall on regions dominated by M31’s light.

Howley et al 2010, in prep
In 2012 a consortium of seven major European research institutes will deliver a new instrument for ESO's Very Large Telescope (VLT) located on the Cerro Paranal in Chile: MUSE (Multi Unit Spectroscopic Explorer) [1]. With its 1'x1' Field of View, a spatial sampling of 0.2" and a spectral sampling of 1.3 Ångström, this Integral Field Unit (IFU) is an ideal playground for studying resolved stellar populations in our own galaxy and beyond. We are going to present first analyses of the potential that comes with the new instrument in this field of research as well as early-stage-implementations of the upcoming pipeline for automatic processing of MUSE exposures.

### Wavelength range: 465 – 930 nm
### Field of View: 59.9" x 60.0"
### Resolving power: 1770 – 3590
### Spatial sampling: 0.20" x 0.21"
### Spatial resolution: 0.61" – 0.41"
### Final data cube: 300x300x3577 px → 1570 MB of data

#### PSF fitting techniques for IFU data
MUSE will be the first integral-field spectrograph to combine a large field-of-view with a high spatial sampling rate. For this reason, it will offer the unique possibility to expand the techniques developed for crowded-field stellar photometry (e.g. Daophot, Stetson 1987 [2]) to IFU data, i.e. to perform spectro-photometry in crowded stellar fields. The plot on the right shows the fraction of recovered stars above a certain S/N level as a function of magnitude. Vertical dashed lines show the results expected for isolated stars.

#### Radial velocities
Radial velocity fits for our grids of synthetic spectra (PHOENIX [3,4] and SYNSPEC [5]) show a high dependency on the spectral types of the stars, especially on the amount of lines in the spectra. But even for hot stars with only few absorption lines the spectral resolution of MUSE is high enough to achieve an error in $v_{rad}$ better than 5km/s for reasonable SN ratios (see plot on the left).

#### Stellar Parameters
Currently we can determine $T_{\text{eff}}$ for a given spectrum with an accuracy of ~200K, but this will presumably increase with the extension of the grids we use for the cross-correlation. As soon as $T_{\text{eff}}$ and log(g) is known, we can start fitting the abundances of single elements. Due to its relatively low spectral resolution, with MUSE those elements will be only Ca, Si, Mg and Fe. But nevertheless we expect to achieve an accuracy of better than 0.2 dex.

### References
A high resolution panoramic study of the structure and substructure of the Milky Way analog NGC 891

Rodrigo Ibata (Strasbourg)

Co-authors: Mustapha Mouhcine, Marina Rejkuba and Bill Harris

We present an analysis of the structure and substructure of the nearby edge-on galaxy NGC 891, based on deep HST/ACS images and an ultra-deep ground-based survey with Subaru/SuprimeCam. These observations resolve stars in the upper two magnitudes of the red giant branch of this Milky Way analogue over a vast area of 90x90kpc, providing the first panoramic view of a spiral galaxy beyond the Local Group. We find evidence for subtle, but very significant, small-scale variations in the median colour and density over the halo area surveyed with ACS. These colour variations are unlikely to be due to internal extinction or foreground extinction, and reflect instead variations in the stellar metallicity. Their presence suggests a startling conclusion: that the halo of this galaxy is composed of a large number of incompletely-mixed sub-populations, testifying to its origin in a deluge of small accretions. Indeed, NGC891 has been caught in the act of accreting a former companion in the SuprimeCam survey: we detect a giant stellar stream that wraps several times around the galaxy. I will also discuss how we are using this stream to understand the large-scale dark matter content in that galaxy.

Left: The inhomogeneities in the median metallicity of stars in the outskirts of NGC 891, derived from a survey with ACS. The upper panel displays the difference between the median metallicity map and a model fit, while the lower panel reports the significance level of the differences. These maps show that the halo has highly significant local variations in the median metallicity.

Right: A much wider-field view from Subaru unveils stellar streams that testify that recent mergers have taken place.

Mouhcine, Rejkuba & Ibata, 2007, MNRAS 381, 873
Galaxy Buildup in the First Gyr: The Nature of Galaxies in the Epoch of Reionization

Garth Illingworth (UCSC)

Co-authors: Rychard Bouwens (UCSC) and the HUDF09 Team

The recent extraordinarily deep WFC3/IR data from the HUDF09 program has dramatically expanded our insight into the galaxy population at z~7-8-9, and given us constraints on the population at z~10. Over 100 z~7-8 galaxies have now been detected. These larger samples have enabled us to undertake a thorough analysis of the luminosity functions at z~7-8 to much lower luminosities than previous studies. We have used the very deepest field data (the HUDF, HUDF09 and the HUDF05 datasets) to derive the contribution to the luminosity density and the star formation rate density from lower luminosity galaxies to as faint as ~0.05L* from z~7=z~4. We have incorporated recent results on the contribution of ULIRGS and sub-mm star-forming galaxies to indicate that in the first 1-2 Gyr the dominant contributors to the star formation rate density in the universe are the lower luminosity, lower mass objects that are fully represented in the Lyman Break population at z~4-7 and at earlier times. Evidence from the HST WFC3/IR and Spitzer IRAC data over the HUDF suggests that these z~7-8 galaxies include older populations that reach back to z>10. I will contrast the striking evolution from z~7-8-9 to z~6 and later, including the stellar population characteristics and the results from recent structural analyses. I will discuss how the broad nature of the galaxy population changes during the period 0.5 billion years to 1-2 billion years, based on the new HUDF09 WFC3/IR data.


Left: The UV luminosity density and star formation rate density over 95% of the age of the universe.
Right: The stellar mass density in the first two Gyr.

Some z~7 galaxies from WFC3/IR.
Feedback and Star Formation: Infrared Insights from 30 Doradus

Rémy Indebetouw: University of Virginia and North American ALMA Science Center, NRAO

Rosie Chen, Geneviève de Messières, Frédéric Galliano, Sacha Hony, Suzanne Madden, Margaret Meixner and the SAGE, SAGE-Spec, and SAGE - 30 Doradus teams

Massive clusters dominate the stellar feedback on galaxies, and massive star formation regions dominate the observed light from galaxies between a few to a few hundred microns. The importance of massive clusters to their galaxies was likely even greater in the era of galaxy assembly and numerous Super-Star Clusters (SSCs), a.k.a likely proto-globular clusters.

Key questions include:
- Why/When/Where do massive clusters form in galaxies?
- How does energetic feedback destroy the natal gas cloud?
- How does energetic feedback encourage or trigger subsequent star formation?

We address these questions in 30 Doradus, our nearest SSC, and other massive star formation regions in the LMC. Infrared photometry provides an unobscured census of current intermediate and massive star formation, and infrared spectroscopic mapping reveals gas and dust physical conditions in the nebula created by the massive stars.

![Image of the galaxy](image)

B:Chandra (Townsley et al. 2006 AJ), G:V, R:8μm IRAC B:[NεIII], G:[NεII], R: 7.7μm PAH

Key findings in broad brush:
- Stars primarily form near previous massive stars, but the 2nd generation contains less mass – feedback can be constructive, but not accelerating, and is primarily destructive.
- Radiative feedback from massive clusters dominates mechanical (both points agree with recent theoretical models)

The investigations of the galaxy star formation histories and chemical evolutions have entered a new area in which high resolution spectrographs on 8m-class telescopes enable detailed analyses of stellar chemical abundances in the Local Group with the same precision as in the Milky Way. Large observational efforts, and in particular our programme DART, revealed the variety of chemical evolution among the dwarf spheroidal galaxies (dSphs) and definitely established their difference from the Galaxy. The recent discovery and analysis of their extremely metal-poor stars ([Fe/H<−3) represents a major step forward in our understanding of how galaxies form and evolve: one can now follow them from their earliest stages of star formation to the most recent events. The benefit of sampling a large variety of galaxies, from the ultra faint dwarfs (UFDs) to the Milky Way is manifold: i) it provides robust tests for models of galaxy formation. Indeed, the interplay between dynamics and star formation results in differences in mean metal enrichment and in abundance ratios. While there are clear evidence that the early enrichment of the ISM by SNe II was universal and independent on the properties of the host galaxy, later stages of galaxy evolution lead to a variety of chemical patterns and differences in their dispersions that appear directly linked to the galaxy mass (Fig1, left). ii) it helps solving open questions of nucleosynthesis, such as for example the production site of the r-process elements. We find clear evidence for differential evolution among the dwarfs in the sense that low mass systems keep low barium abundances up to high metallicities, at variance with larger galaxies. Due to their low binding energy, the small dSphs could well loose the main r-process products synthesized in massive stars (Fig2, right).

Black points show the Milky Way stars, red, blue and green indicate the Fornax, Sculptor and Sextans stars respectively. The open symbols represent the UFDs, Carina and Draco.
Barium Abundances in Open Clusters

Heather R. Jacobson (MSU) & Eileen D. Friel (Lowell Observatory)

We have begun a study of neutron-capture element abundances in a large open cluster sample. Recent work by D'Orazi et al. (2009) has revealed an unexpected trend of increasing [Ba/Fe] ratios as a function of decreasing age in a sample of 20 open clusters. Such a trend cannot be reproduced by chemical evolution models using standard s-process Ba yields. We have determined Ba abundances for eleven clusters ranging in age from 1 to 10 Gyr using high resolution echelle spectroscopy and a spectrum synthesis technique. Our preliminary results for this sample also show a trend of increasing [Ba/Fe] with decreasing age. This confirmation of the D'Orazi et al. result, using a different cluster sample and analysis technique, supports their suggestion that s-process Ba production in low mass AGB stars increases as a function of decreasing initial stellar mass.

Left: [Ba/Fe] versus age for our open cluster sample (for sample details see Friel et al. 2010).

Right: (Taken from D'Orazi et al. 2009.) [Ba/Fe] versus age for the cluster sample of D'Orazi et al. (2009; circles) and field stars of Bensby et al. (2005; triangles). A chemical evolution model using standard s-process yields (blue line) fails to reproduce the observed trend with age. A model that incorporates enhanced yields in low-mass AGB stars (green line) better matches the results. Our results are in good agreement with these findings.

Friel et al. 2010 AJ, 139, 1942
Signatures of hierarchical structure formation in stellar populations.

Kathryn V Johnston (Columbia University)

Above: Projections of surface brightness, metallicity and alpha-elements of model stellar halos built entirely from accretion events within a consistent cosmological context (see Bullock & Johnston, 2005, Font et al 2006a). Each panel is 300kpc on each side. Image credit: Sanjib Sharma.

Stars that make galaxies are expected to form within dark matter halos that are themselves growing through gravitational collapse and mergers. This scenario implies a rich interplay between the simple collisionless dynamics of the dark matter and the complex baryonic physics that shapes the galaxies. In this talk I will review known characteristics of abundance patterns in the Local Group that are believed to reflect this interplay, and look ahead to future prospects for this work.

For example, simulations of stellar halos forming in a cosmological context entirely from accretion events show trends in satellite and debris stream stellar populations that are consistent with past and current observations: the satellites generally have lower alpha element abundances than their host halos (Robertson et al 2005, Font et al, 2006a), as seen in high-resolution spectral studies (e.g. Venn et al 2004); the highest surface brightness debris streams are often more metal rich than the bulk of their host halos, as observed around both M31 and the Milky Way (Font et al 2006b, Gilbert et al 2009). The simulations predict that streams that are still coherent in space are likely to have lower alpha-elements abundances than their hosts (Font et al 2006b). These trends can be explained as natural consequences of the differences between timescales for hierarchical buildup, debris dispersal and chemical enrichment within different mass dark matter halos. Future surveys promise to allow us to move beyond these simple consistency checks of general trends and use Local Group objects as local laboratories for testing the baryonic physics of galaxy formation in much greater detail.

Bullock & Johnston, 2005
Font et al 2006a, 638, 585
Venn et al 2004, AJ 128, 1177
Population Study of Resolved Stars in M83 using HST/WFC3 Early Release Science Data

Hwi hyun Kim (ASU)

Co-authors: Brad Whitmore (STScI), Rupali Chandar (Univ. of Toledo), Abhijit Saha (NOAO), Catherine Kaleida (ASU), Rogier Windhorst (ASU) and WFC3 SOC Team

We present a multi-wavelength photometric study of individual stars in M83 based on observations taken as part of the WFC3 Early Release Science (ERS) program. The central region of M83 has been imaged in seven broad-band filters to obtain multi-wavelength coverage from the ultra-violet to near-infrared. We use four filters—F336W, F438W, F555W, and F814W—to measure the effective temperature and intrinsic luminosity for ~10,000 stars. These measurements are used to determine the recent (<1 Gyr) star formation history of M83. We selected 29 regions in the spiral arm and the inter-arm area of M83 and categorize them based on their H α morphology. To determine ages of stars in each region, we use color-magnitude diagrams (CMD) and two-color diagrams with the Padova Isochrones for a metallicity of Z=0.03 (1.5 Z_☉) overlaid, and compare to ages determined by cluster age-estimates from H α morphology and from SED fitting. The CMD and color-color diagrams of resolved stars from the multi-band HST/WFC3 observations of M83 indicate the presence of multiple stellar populations: the recently formed main-sequence, He-burning blue-loop, red giant branch, and asymptotic giant branch stars. Multi-populations of stars in the CMDs of the 29 selected regions indicate that stars in a single region may not have formed from the same star formation event. Also, we find that the regions with ages determined younger than 10 Myr are located preferentially along the active star-forming region on the spiral arm.

Left: HST WFC3/UVIS composite of F336W+F555W+F814W (broad bands) and F502N+F657N (narrow bands) images with 29 selected regions overlaid.
Right: CMDs of M_{F814W} vs. (F555W-F814W). The distance modulus of (m-M) _V = 28.29 mag was used to calculate the absolute magnitude. Padova isochrones for Z=0.03 are over-plotted for ages of 4, 10, 15, 30, 60, and 100 Myrs. The region classification for each category of H α morphology is described in red above the image cut-outs.
Tracers of stellar mass-loss: optical and IR colors and SBFs

Rosa A. González Lópezlira (CRyA, UNAM, Mexico)

Co-authors: Gustavo Bruzual-A., Stéphane Charlot, Javier Ballesteros-Paredes, & Laurent Loinard

We present optical and IR integrated colors and surface brightness fluctuation (SBF) magnitudes, computed from stellar population synthesis models that include emission from the dusty envelopes surrounding TP-AGB stars undergoing mass-loss. We explore the effects of varying the mass-loss rate (MLR) by one order of magnitude around the fiducial value, modifying accordingly both the stellar parameters and the output spectra of the TP-AGB stars plus their dusty envelopes. We compare these models to optical and IR data of single AGB stars and Magellanic star clusters. Neither broad-band colors nor SBF measurements in the optical or the near-IR can discern global changes in the MLR of a stellar population. However, we predict that mid-IR SBF measurements can pick out such changes, and actually resolve whether a relation between metallicity and mass-loss exists.

Left: SBF measurements vs. age of young and intermediate-age MC clusters, compared to models with $Z = 0.008$ and different mass-loss rates. Colored regions delimit expected $1\sigma$ stochastic errors for SSPs with 0.5 million solar masses. **Green-vertical-hatched**: standard CB09; **blue-left-hatched**: fiducial MLR; **cyan-horizontal-hatched**: fiducial MLR/10; **red-right-hatched**: fiducial MLR x 10. **Solid circles**: $V$ and $I$ SBF measurements for globular clusters (Raimondo et al. 2005); **empty triangles**: and near-IR SBFs for artificial MC ‘superclusters’. **Optical and near-IR SBFs are not sensitive to different MLRs of entire populations.**

Right: Preliminary reduction (solid circles) of Spitzer observations of intermediate-age MC ‘superclusters’, compared to models with $Z = 0.004$ and different mass-loss rates (González-Lópezlira et al. 2010, in preparation). **Mid-IR SBFs can pick out different global mass-loss rates of entire populations; stars with higher MLRs start to show up at longer wavelengths.**


CB09 models
Large spiral galaxies have to come from somewhere, and the currently favored model prefers the accretion of satellite galaxies to monolithic collapse. Although the accreted galaxies are now dissolved, some of their counterparts still exist today in various states of dissolution. Images and spectroscopy of the resolved stellar populations of surviving satellite galaxies of the Milky Way and other large, nearby galaxies are windows into the seeds of galaxy formation. I review the state of knowledge of the ages, metallicities, detailed chemical abundances, and kinematics of surviving satellite galaxies. I compare these to the stellar populations of galactic halos, mostly of the Milky Way and M31. The comparison leads to the conclusion that the stellar populations of large galaxy halos are consistent with the accretion of smaller galaxies.

*Left*: Trends of different [$\alpha$/Fe] ratios in Milky Way dwarf satellite galaxies (colored lines) compared to the Milky Way halo (dashed line). Although analogs to these dwarf galaxies are thought to comprise the halo, the detailed elemental abundances differ between the two populations. Different rates and intensities of star formation possibly account for the variance. These measurements are based on Keck/DEIMOS spectroscopy (Kirby et al. 2010, ApJ, submitted).
Star cluster formation is not limited to ‘classical’ environments such as galactic spiral arms. Observations find them in all types of settings, supporting the existence of a single ‘mode’ of sub-galactic structure formation: clustered star formation. In that way, clusters maintain a close link to the overall activity in a system and as such can be used to trace the star formation history of a galaxy. Furthermore, their brightness enables observations of clusters in faraway systems. This talk will present studies of clusters in a variety of environments, from starburst cores to intergalactic space. I will discuss our thorough spectroscopic and photometric measurements of age, metallicity, extinction and mass of stellar populations in the disk and nucleus of M82, the tidal tails of NGC 6872 and the Antennae, as well as two very different galaxy groups, Stefan's Quintet and Hickson Compact Group 7. Star clusters provide important information about each of these host systems - information that is not easily discernible using conventional methods. Thus, we learn much about the state of each host, with the added bonus of enhancing our understanding of cluster formation and evolution.

The age distribution of ~50 star clusters spanning the disk and nucleus of M82, as derived from our multi-object spectroscopy (Konstantopoulos et al., 2008, 2009). Clusters represent the ‘tip of the iceberg’ in terms of the hierarchical process of star formation and can therefore be used as tracers of star formation history. This plot shows the procession of different stages in the starburst history of M82, from the interaction that triggered it some ~220 Myr ago, all the way to the quenching in the disk in recent times. In addition to cluster ages, measurements of mass, extinction, metallicity and radial velocity are also used to derive the history, present state and future evolution of the host system.

Similar to the situation at low redshift, the properties of galaxies beyond $z=2$ are strongly correlated. Massive galaxies at this epoch clearly separate into two classes: the large star-forming galaxies that form the blue cloud, and the smaller quiescent galaxies on the red sequence. Thus, it is evident that a Hubble sequence with strongly correlated galaxy properties is already in place beyond $z=2$. Nonetheless, this sequence does not resemble the local Hubble sequence, as the structures and morphologies of the $z>2$ galaxies are different from their local analogs. While quiescent galaxies are much more compact than nearby early-type galaxies, massive star-forming galaxies have irregular and clumpy structures. I will discuss the origin of the $z=2$ Hubble sequence, and its evolutionary connection to the local Hubble sequence.

**Left:** rest-frame $U-B$ color vs. stellar mass for a massive galaxy sample at $z \sim 2.3$ with rest-frame optical spectroscopy. We use the HST NIC2 images as symbols. The color coding reflects the specific SFR of the galaxy. The emission-line galaxies can be recognized by their italic ID numbers, and A indicates the AGNs. The galaxies clearly separate into two classes: the large (irregular) star-forming galaxies in the blue cloud, and the compact, quiescent galaxies on the red sequence. **Right:** stacked SEDs, composed of the rest-frame UV photometry and rest-frame optical spectra of all blue (bottom panel) and red galaxies (top panel) at $2 < z < 3$ in our spectroscopic sample. We also show the stack and full range of best-fit stellar population synthesis models (Figure from Kriek et al. 2009, ApJ, 705, L71)
The IMF of simple and composite populations

Pavel Kroupa (AlfA, Bonn)

The stellar IMF is the distribution function of stellar masses born together in one causally connected event within a spatial region of not more than a few pc in extend. It cannot be measured in any system, but statistical methods combined with corrections for dynamical bias allows one to infer the existence of a universal canonical IMF as the parent distribution from which the various simple stellar populations are drawn. There is no evidence for variation of the IMF (Kroupa 2008; Bastian et al. 2010) except at the highest star-burst cluster masses above $10^6$ Msun. Here the high mass-to-light ratio of ultra-compact dwarf (UCD) galaxies may suggest top-heavy IMFs in the extreme environments of UCD formation (Dabringhausen et al. 2010).

The IMF in a whole galaxy is, in contrast, that of a composite population such that the IMFs of the individual simple populations must be added (Haas & Anders 2010). This leads to an integral over the currently forming star cluster population and implies the integrated galactic IMF (IGIMF) to be top light. The steepness of the IGIMF for massive stars can be shown to depend on the star formation rate of the galaxy (Weidner & Kroupa 2005). This leads to an entirely new avenue of understanding galaxy evolution: The galaxy mass-metallicity relation emerges naturally (Koeppen et al. 2007; Recchi et al. 2009) and the gas-consumption time scales of all galaxies become similar (about 3 Gyr), such that late-type dwarf galaxies and massive disk galaxies turn out to have the same “star formation efficiencies”. This challenges our current understanding of galaxy evolution.

Evolution Similarities among the RR Lyrae in Oosterhoff I and II Globular Systems

Andrea Kunder (CTIO)

Co-authors: A. Walker, P.B. Stetson, J.M. Nemec, G. Bono, G. Andreuzzi, S. Cassisi, R. De Propris, M. Dall’Ora, M. Monelli

We present a comparison of various intrinsic properties of a subsample of Oosterhoff I and Oosterhoff II clusters (Ool and Ooll) to discuss the possible explanation that RR Lyrae variables in Ooll clusters are more evolved than those in Ool. From the Ool cluster IC 4499 and the Ooll cluster M15, it is found that the RR Lyrae temperatures are within 250 K at minimum light. If variables in Ooll clusters are more evolved than those in Ool clusters, this temperature similarity must be explained.

Period-change rates give insight on the evolution of RR Lyrae variables; the period of an RR Lyrae should increase if the star evolves from blue to red in the HR diagram and decrease if the star evolves from red to blue. New period change rates for the RR Lyrae in the Ool cluster IC 4499 are found. There is a clear preponderance for a period increase, contrary to the explanation that Ool RR Lyrae evolve from red to blue.

The period-change rates as a function of position in the period-amplitude plane are used to examine evolutionary effects in Ool and Ooll clusters, field RR Lyraes and the mixed-population cluster ω Centauri. It is found that there is no correlation between evolutionary state and the typical definition of Oosterhoff groups. The RR Lyrae period changes do not conform to the hypothesis RR Lyrae variables in Ooll systems are evolved HB stars that spend their ZAHB phase on the blue side of the instability strip. This suggests that age may not be the primary explanation for the Oosterhoff types.

Left: The period-amplitude diagram of RR Lyrae in IC 4499. The period change rates, β, are also indicated (plus sign indicates increasing period, and minus sign indicates decreasing period). The green triangles designate possible Blazhko variables.

Right: The period-amplitude diagram of RR Lyrae in Ool GCs with determined period change rates.
Panchromatic Estimation of Star Formation Rates in Galaxies at $1<z<3$
Peter Kurczynski (Rutgers University)

Co-authors: Eric Gawiser, Minh Huynh, Rob J. Ivison, LESS Collaboration, MUSYC collaboration

We utilized the rest-UV-through-radio Spectral Energy Distributions (SEDs) of a sample of BzK galaxies to determine their average star formation rates and dust temperatures. Galaxies were separated into bins of photometric redshift. In order to obtain panchromatic SEDs for each set of galaxies, we performed stacking analyses in Spitzer-MIPS (24, 70 μm) data. We also stacked sub-millimeter (250, 350, 500 μm from BLAST; 870 μm from the Laboca ECDF-S Sub-millimeter Survey, LESS), using a new stacking algorithm (Kurczynski and Gawiser 2010), and radio (VLA 1.4 GHz and GMRT 610 MHz) data. Our estimates of bolometric IR luminosity utilized photometric data that spanned the entire peak of the dust emission spectrum, and thus improved upon previous single band estimators of IR luminosity. We combined UV continuum and bolometric IR star formation rate estimators and found redshift binned, average star formation rates of $29-130$ M$_{\odot}$ yr$^{-1}$, increasing with median redshift from 1.3-2.7. Our results imply somewhat diminished dust obscuration at high redshift.

Left: BzK diagram (z-K vs. B-z color) of K-selected, star forming galaxies in ECDF-S from MUSYC. Magnitudes are in the AB system. Galaxies were chosen for redshift binned stacking analyses and are illustrated as follows: Circles (red) 0.9<z<=1.2 (49 objects), Triangles (green) 1.2<z<=1.5 (161 objects), Squares (blue) 1.5<z<=2.0 (233 objects), Stars (plum) 2.0<z<=3.3 (154 objects). AGN are excluded by requiring non-detections in the Chandra ECDF-S catalog. Right: Panchromatic SEDs for redshift binned sBzKs in the range (top left) 1.0<z<=1.5, (top right) 1.5<z<=2.0, (bottom left) 2.0<z<=2.5, (bottom right) 2.5<z<=3.3. The broad, central peak in each spectrum corresponds to thermal dust emission. These emission peaks are sampled in FIR-sub-millimeter data by Spitzer MIPS (24, 70 μm), BLAST (250, 350, 500 μm) and LABOCA (870 μm).

Kurczynski and Gawiser, 2010 AJ 139 1592.
Spitzer Analysis of HII Region Complexes in the Magellanic Clouds: Determining a Suitable Monochromatic Obscured Star Formation Indicator

Brandon Lawton (STScI), Karl D. Gordon (STScI), the Spitzer SAGE-LMC Legacy Team, and the Spitzer SAGE-SMC Legacy Team

HII complexes are the birth places of stars, and as such they provide the best measure of current star formation rates in galaxies. The close proximity of the Magellanic Clouds allows us to probe the nature of these star forming regions at small spatial scales. Star formation rates are calculated using a tracer of the UV photons from young massive stars. HII complexes will have some fraction of their UV photons obscured by dust and some fraction unobscured. For obscured HII complexes, the bolometric infrared flux (TIR, 8-500 μm) can be used to recover the extinguished UV photons (Kennicutt 1998). However, observers do not always have the luxury of a bolometric observation and frequently use a monochromatic IR band in its place. In this work we aim to determine which of the Spitzer IR bands best traces the TIR and thus is a suitable monochromatic star formation indicator.

We present the spatial analysis, via aperture/annulus photometry of 16 LMC and 16 SMC HII complexes using the Spitzer IRAC (3.6, 4.5, 8 μm) and MIPS (24, 70, 160 μm) bands. The results are as follows:

1) the SEDs of the star forming regions peak near 70 μm at most radii;
2) the HII region sizes depend upon which dust component is measured, and the sizes measured via 70 μm (~70 pc in radius) are nearly identical to the sizes measured via the TIR;
3) the radial 24 μm fluxes, normalized by the TIR, is peaked in the center of HII complexes;
4) the radial 8 and 24 μm fluxes, normalized by the TIR, are dependent on the host galaxy in that they are weaker at all radii in the SMC relative to the LMC;
5) the radial 70 μm fluxes, normalized by the TIR, remain relatively constant (~45% x TIR) from 10-400 parsecs;
6) the radial 160 μm fluxes, normalized by the TIR, are highly peaked in the outer radii; and
7) the 1-sigma standard deviations of the normalized 70 μm fluxes are a lower fraction of the mean (0.05-0.12 depending on radii), than the normalized 8, 24, and 160 μm fluxes (0.15-0.52).

From these findings we argue that 70 μm is the most suitable IR band to use as a monochromatic obscured star formation indicator for the spatial scales measured in this work (10-400 pc radii). We use our results to modify the TIR-SFR equation from Kennicutt (1998) to use 70 μm luminosities where,

\[
\text{SFR (M}_\odot \text{ yr}^{-1}) = 9.7(0.7) \times 10^{-44} \text{ L}_\odot \text{ (ergs s}^{-1}).
\]

Biases in Constraining the Stellar Population Properties of High-redshift Star-forming Galaxies: Dependence on Star-formation Histories

Seong-Kook Lee (Johns Hopkins University)

Collaborators: Henry C. Ferguson (STScI), Rachel S. Somerville (STScI), Tommy Wiklind (STScI), Mauro Giavalisco (UMass)

Powerful facilities -- such as Hubble Space Telescope/ACS and new WFC3 -- provide us unprecedented opportunity for probing and investigating high-redshift galaxies. This progress is expected to advance with the upcoming powerful JWST. One significant difference between the studies of local or low-redshift galaxies and those of high-redshift galaxies is that we cannot see the resolved individual stars or stellar clusters, but only the integrated light from entire stellar and ISM component of a given galaxy. Thus, for an investigation of these high-redshift galaxies, we need a tool for estimating the stellar populations of these galaxies from their integrated light.

One widely used technique is to fit models to the spectral energy distributions (SEDs) as measured via broadband photometry. A problem that is not widely appreciated is that the inferences for stellar masses, ages, star-formation rates, and dust contents thus derived are not only uncertain, but also tend to be highly biased. We show the patterns of biases in SED-fitting analysis with various forms of SFHs used and demonstrate that increasing SFHs are more relevant forms of SFHs than (widely-used) exponentially declining ones in SED-fitting analysis of high-redshift (3 < z < 6) star-forming galaxies. We also present the results of the principal component analysis (PCA) of star-formation histories of high-redshift star-forming galaxies from semi-analytic models of galaxy formation. Principal component analysis: (1) reveals that in current galaxy formation models, representative star-formation histories of star-forming galaxies at high-redshift are increasing ones, and (2) confirms that the patterns and amounts of biases in SED-fitting depend on intrinsic SFHs of galaxies.

References
**ABSTRACT**

The Sloan Digital Sky Survey III/APOGEE (SDSS-III/APOGEE) is a large-scale spectroscopic survey of Galactic stars. The SDSS-III/APOGEE will obtain high-S/N, R ~ 30,000 spectra, covering the 1.51 to 1.68 micron range for order 100,000 stars. APOGEE will target stars in all components of the Galaxy, including the halo, bulge, disk, and tidal streams. APOGEE will be the deepest chemodynamical survey of the bulge and disk stellar populations, and amass substantial samples from the other Galactic components. With abundances for at least 15 elements accurate to ~0.1 dex and radial velocity accuracies of ~0.3 km/s, APOGEE will provide fundamental constraints on galaxy evolution models and lend insights into the physical processes leading to the formation of the Galaxy.

**CORE SCIENCE GOALS**

- First 3-D MW chemical abundance distribution (for ~15 elements).
- Metallicity distribution functions across disk, bulge, halo (Fig. 4).
- Constrain the IMF and SFH of bulge/disk as function of radius, metallicity/age, chemical evolution of inner Galaxy.
- Determine nature of Galactic bar and spiral arms and their influence on abundances/kinematics of disk/bulge stars.
- Measure Galactic rotation curve from stars of known distance.
- Search for/parse chemistry/kinematics of halo substructure, especially at low-latitude – e.g., the Monoceros Ring.
- Combine APOGEE spectroscopic parallaxes with optical, NIR and MIR data to make Galactic dust distribution (Fig. 2) and constrain variations in the extinction law.
- Systematic probe of Galactic star clusters.
- Search for rare populations, place constraints on first stars.

**APOGEE IN A NUTSHELL**

- Dedicated 300 fiber, cryogenic, near-infrared spectrograph.
- R = 27,500 – 31,000, S/N = ~100/pixel, H-band (1.51-1.68um) spectra of ~10^3 field and cluster giants down to H~12.5.
- Also, some additional deeper (H ~ 14.1) and special target probes.
- Majority fraction of bright-time nights on the SDSS 2.5-m telescope over 3 years of SDSS-III starting in April 2011.
- Accurate radial velocities (to 0.3 km/s) and precision (0.1 dex) abundance patterns for the entire sample.
- Focus on H band allows deeper probe of the dust-extinguished Galactic bulge and disk than any other survey planned.
- At H=13.5, can reach giant stars as far as ~70 kpc in Galactic halo and 25 kpc through A_V~2.5 (A_V~15) of dust.
- Red giant/clump stars reliably selected from 2MASS (Fig. 1).
- Will increase by orders of magnitude the number of available high-resolution stellar spectra, especially at low V (Fig. 2).
- Apart from critical elements ([Mg, Si, S, Ca, Ti, Cr, Al, Fe, Na, K], Fe-peak, Ti, Mn, Wo, Co) and possibly neutron-capture (Ce, Nd) elements (Fig. 5) with a pipeline reduction code.
- Public data releases will include fully reduced and calibrated spectra as well as pipeline-derived, high level data (RVs, RV variability, stellar parameters, abundances) for all stars.

**CURRENT STATUS**

- Funded by NSF, Sloan Foundation, and SDSS-III institutional partners.
- APOGEE spectrograph in construction stage.
- APOGEE spectrograph building constructed on-site, adjacent to Sloan 2.5-m Telescope.
- Data reduction and stellar parameters/abundance analysis pipelines under construction.
- Main survey field selection being finalized (e.g., Fig. 3).
- Target selection criteria being finalized (Figs. 1, 4).
- First light on telescope expected late 2010.
- First survey observations expected April 2011.

**Figure 2:** All-sky distribution of 2MASS point sources with the Galactic bulge (yellow) and disk (cyan). The gray overlay marks the area with A_V~1, a large fraction of which is inaccessible to efficient exploration with optical surveys on even the largest telescopes. Because A_V~1, APOGEE is the only survey currently planned that can reach deep into the Galactic bulge and disk to obtain spectra of large numbers of (dust-obscured) targets.

**Figure 3:** Schematic representation of current plan for low-latitude APOGEE pointing strategy in celestial (top) and Galactic (bottom) coordinates. Also shown are positions of SEGUE calibration fields and known star clusters. APOGEE fields at low declination are smaller due to differential rotation effects, but still contain full complements of bulge/disk targets. Nominal exposures will be 3 hours total, but some fields will be visited for 10 or 30 hours to probe more deeply and/or build up larger numbers of targets.

**Figure 4:** Model of the expected distribution of APOGEE targets, color-coded to bulge, halo, thin and thick disk stars based on the targeting plan shown in Fig. 3, an H=12.5 survey limit and the TriLegal Milky Way model. (Top panel) Galactic plane view. (Bottom panel) Distribution by R^25 and z^25.
**Stellar Populations in the Cosmological Context**  
**STScI May Symposium (2010)**

**The Predictive Power of Galaxy SED Models at Intermediate Redshifts**

Danilo Marchesini (Tufts University)

Our knowledge of the properties of galaxies at intermediate redshifts (e.g., 1<z<4) is mostly based on the modeling of the observed spectral energy distributions (SEDs) of galaxies from broad-band photometry using stellar population synthesis models. This technique has allowed us to study large samples of galaxies, to derive their stellar population properties, such as stellar mass and star formation rate, and to study the evolution of these properties as a function of cosmic time. I review some of these results (with an emphasis on the evolution of the stellar mass content of the universe), highlighting the power of SED modeling and its current limitations when applied to distant galaxies. Specifically, I discuss the effects of different SED-modeling assumptions on the estimated stellar masses, namely the initial mass function, the stellar population synthesis model, the metallicity, the extinction curve, and the star formation history, showing that, with current dataset, the total error budget has now become entirely dominated by systematic uncertainties at all redshifts z<4. Therefore, the analysis of systematic errors has to become a very high priority in all those studies wishing to understand the stellar mass content of the universe and its evolution with cosmic time. Deep near-infrared spectroscopic observations of complete and representative samples of galaxies at z>1.5 are crucial and desperately needed for calibrating stellar masses at high-redshifts and for testing the validity of the stellar masses inferred from SED modeling, as well as directly constraining the IMF, determining stellar ages, metallicities, relevance of star bursts, and star-formation rates.

**Left:** Stellar mass functions of galaxies at 1.3<z<2.0 derived from the MUSYC+FIREWORKS+FIRES surveys (Marchesini et al. 2009) and adopting different SED-modeling assumptions, including different IMFs, metallicities, extinction curves, and stellar population synthesis models.

**Right:** Stellar mass function of galaxies at 3<z<4 measured from the NEWFIRM Medium-Band Survey (colored symbols; Marchesini et al. 2010). With current dataset, the stellar mass function error budget at z<4 is now entirely dominated by systematic uncertainties due to different SED-modeling assumptions adopted to derive stellar masses.

A survey of Stellar Tidal Streams in Nearby Spiral Galaxies

David Martinez-Delgado (MPIA)

Within the hierarchical framework for galaxy formation, minor merging and tidal interactions are expected to shape large galaxies to this day. As part of a pilot survey, we have carried out ultra-deep, wide-field imaging of some isolated spiral galaxies in the Local Volume with data taken at small (0.1 to 0.5-meter diameter), robotic telescopes that provide exquisite surface brightness sensitivity. Our observational effort has led to the discovery of previously undetected giant stellar structures in the halos of these galaxies, likely associated with debris from tidally disrupted satellites. In addition, we confirm several enormous stellar over-densities previously reported in the literature, but never before interpreted as tidal streams. Our collection of galaxies presents an assortment of tidal phenomena exhibiting strikingly diverse morphological characteristics. In addition to identifying great circles-like features that resemble the Sagittarius stream surrounding the Milky Way, our observations have uncovered enormous structures that extend tens of kiloparsecs into the halos of the central spiral. We have also found remote shells, giant clouds of debris within galactic halos, jet-like features emerging from galactic disks and large-scale, diffuse structures that are almost certainly related to the remnants of ancient, already thoroughly disrupted satellites. Our comparison with available stellar halo simulations set in a Lambda-Cold Dark Matter cosmology suggests that this extraordinary variety of morphological specimens detected in our survey could represent one of the first comprehensive pieces of evidence to support that the hierarchical formation scenarios predicted by these theoretical models apply generally to galaxies similar to the Milky Way in the Local Volume.

Left: Luminance filter images of nearby galaxies from our pilot survey showing large, diffuse light substructures in their outskirts:
(a) a possible Sgr-like stream in Messier 63;
(b) giant plumes around NGC 1084;
(c) partial tidally disrupted satellites in NGC 4216;
(d) an umbrella shaped tidal debris structure in NGC 4651;
(e) an enormous stellar cloud in NGC 7531;
(f) diffuse, large-scale and more coherent features around NGC 3521;
(g) a prominent spike and giant wedge-shaped structure seen emanating from NGC 5866;
(h) a strange inner halo in NGC 1055, sprinkled with several spikes of debris (RdS 0.5-meter).

A color inset of the disk of each galaxy has been over plotted for reference purposes (see Martinez-Delgado et al. 2010).

Stellar Populations of Dwarf Early-Type Galaxies in the Coma Cluster

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We compare star formation histories of dwarf elliptical (dE) and dwarf lenticular (dS0) galaxies in two regions of different density in the Coma cluster. To study the star formation histories, we measure line strength indices for ~70 dE/dS0 galaxies in the core of the Coma cluster and a SW field, part of which overlaps with a region believed to be infalling into the cluster. We use Lick/IDS line-strength indices in combination with stellar population models (SPMs) to derive ages, metallicities, and chemical abundances for these galaxies. We investigate the relations between each index and velocity dispersion, \( \sigma \), for our dE/dS0 galaxies and find that majority of metallicity-dependent indices cannot be described by linear relations with \( \sigma \) (Group I in Figure 1). We find no connection between either age, metallicity, [\( \text{\#}/\text{Fe} \)], or the chemical element each line strength is most sensitive to, with the shape of the Index-\( \sigma \) relations. The indices that exhibit linear relations with \( \sigma \) (Group II, in Figure 1) seem to be independent of microturbulent velocity of stellar atmospheres (Trippico & Bell 1995).

Galaxies in the core of the cluster are on average younger, less metal-rich, and have lower \( \sigma \)-ratios (Figure 2). We find an unusually high fraction of dE/dS0 galaxies with supersolar [\( \text{\#}/\text{Fe} \)] ratios for these galaxies in the SW region, although a number of dE/dS0s in the center also show high [\( \text{\#}/\text{Fe} \)]. Supersolar [\( \text{\#}/\text{Fe} \)] ratios imply short time scales for star formation histories, comparable to more massive ellipticals, while the range in age and metallicity suggests that some of these dE/dS0 galaxies have formed their stars more recently.
The Formation of Spiral Spheroids and Their Globular Cluster Systems

Aparna Maybhate (STScI)
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Two main scenarios for building bulges in spiral galaxies are currently popular: Merger-driven formation by dissipative merging and secular evolution of inner disk stars. The former process involves the formation of massive metal-rich star clusters, while the latter does not. In order to discriminate between these two processes of bulge formation, we use deep, HST images taken with the ACS/WFC in the F475W and F814W filters to detect and study the globular cluster systems in four edge-on Sa galaxies: NGC 5475, NGC 4710, NGC 5308, and NGC 4866. These cover a factor of 4 in luminosity, and hence in mass. We see a clear trend of increasing red cluster fraction with increasing bulge luminosity in these galaxies. This indicates that merging processes played a major role in the formation of the bulges in these early-type spirals. We also find that the specific frequency of blue clusters is consistent with typical specific frequency values for later-type spirals.

**Left:** The relation between the total galaxy luminosity and the specific frequency of the clusters. Filled circles and crosses denote the total $S_N$ and the $S_N$ of the blue clusters. Note that the $S_N$ of the blue clusters lies within the range of values seen in late-type spirals.

**Right:** The relation between the bulge luminosity and the fraction of red clusters. The blue circles are ellipticals from Peng et al. (2006), red squares and magenta squares are the observed values for the target Sa galaxies and comparison early-type spirals from Goudfrooij et al. (2003). The dashed lines are models for expected values of red fractions for various values of $B/T$.

The Pan-Andromeda Archaeological Survey

Alan McConnachie (Dominion Astrophysical Observatory)

and the PAndAS Collaboration

The Pan-Andromeda Archaeological Survey (PAndAS) is contiguously surveying >300 square degrees surrounding M31 and M33, reaching to a maximum projected radius of 150kpc and 50kpc from the centers of these galaxies, respectively. This photometry reaches approximately 4 magnitudes below the tip of the RGB, allowing the identification of RGB stars (and their classification by photometric metallicity), AGB stars and young stellar populations (in the disks of our two targets). After a few years of data, the main body of the survey is now complete and the northern and southern hemispheres have been mapped to comparable depth over comparable areas (see Figure 1 for a southern hemisphere map). A new large scale structure surrounding M33 has been discovered (shown in Figure 2, extending down to \(~33\text{mags/sq.arcsec}\) and is evidence for an interaction between M33 and M31 approximately 2 - 3 Gyrs ago; modelling of this feature helps constrains M31’s transverse motion. Numerous new dwarf galaxies have been discovered (now up to AndXXVII), as well as new large stellar streams, some of which have identifiable progenitors (such as AndI and NGC147), and some with no clear progenitor. This unique panoramic view of an L* galaxy system is now being quantified from a global perspective, specifically in terms of the 2D shape of the stellar halo out to very large radius, and an analysis of the statistical distribution of substructure.

Figure 1: The PAndAS density distribution of red giant branch stars in the surroundings of M31.

Figure 2: Same as Figure 1, but now optimized for stars belonging to a vast structure surrounding M33 and shown as a contour plot (the lowest level contour is at a surface brightness of \(~33\text{ mags sq.arcsec}\)).

McConnachie et al., 2009, Nature, 461, 66
The Stellar Populations of M32: Resolving the nearest elliptical with HST ACS/HRC

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We present the deepest optical color-magnitude diagram (CMD) to date of M32, obtained from deep F435W (~ B) and F555W (~V) photometry based on HST ACS/HRC images. The CMD of M32 goes as deep as F435W ~ 28.5 at 50% completeness level. The detection of a blue plume (BP) and blue loop (BL) stars reveal for the first time the presence of very young stellar populations in M32. We also report the detection of a red giant branch bump (RGBb) and an asymptotic giant branch bump (AGBb) which, together with the red clump (RC), allow us to constrain the age and metallicity of the M32 dominant population in our fields. The CMD of M32 displays a wide color distribution of RGB stars indicating an intrinsic spread in metallicity. Bright AGB stars, as well as the strong RC, indicate the presence of intermediate age populations in M32. There is not a noticeable presence of blue horizontal branch (BHB) stars, suggesting that an old metal-poor population does not significantly contribute to the light or mass of M32 in our observed fields. However, RR Lyrae variables found in our fields confirm the presence of an ancient population in M32.

Left: The Hess diagram of M32. The boxes highlight features that reveal the different stellar populations of M32. The RGBb, AGBb and RC positions in the CMD indicate that the mean age of M32 in our observed field is in between 5 and 10 Gyr. The dashed line indicates the 50% completeness level. Middle: Padova isochrones of young ages (0.4, 0.5, 0.7, 1 and 1.5 Gyr) and metallicity [Fe/H] = -0.3, superimposed to the CMD of M32, suggest the presence of ~ 0.7 Gyr old stars in this galaxy. Diamonds indicate RR Lyrae variables detected in our fields. Right: Metallicity distribution function of M32. It peaks at [Fe/H] ~ -0.2. Note that there are few stars with [Fe/H] < -1.2.

The ALHAMBRA-Survey: Photometric Stellar Masses

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Co-authors: Francisco Prada (IAA-CSIC) and the ALHAMBRA Collaboration

ALHAMBRA is an ongoing photometric survey primarily designed for the study of the evolution of the properties of galaxies from z~1. It will map a region of ~4 sq. deg. down to magnitude $I_{AB} \sim 25$ with a set of 20 filters that cover the entire optical range plus the J, H, K bands in the NIR. Featuring a combination of depth and spectral resolution, ALHAMBRA has the potential to shed light on the average evolution of stellar populations from the time when the cosmic star formation rate is known to peak. We have compared the ALHAMBRA population of galaxies at low redshift with the SDSS, by using synthetic SDSS bands and selecting a sample of galaxies with $0.1 < z < 0.3$ and $i_{SYN} < 20$. Our results show an excellent agreement in the color and magnitude distributions as compare with the SDSS. We present here first estimates of photometric stellar masses, obtained using the Flexible Stellar Population Synthesis code (Conroy et al. 2009) for the same low-redshift sample. Although the stellar population fitting is still preliminary, the distributions of mass-to-light ratios and stellar masses obtained so far are, on average, consistent with what we expect from the nearby Universe. This low-redshift calibration is a necessary step before we can focus on the evolution of the ALHAMBRA population of galaxies from z~1.

**Left and Middle:** Spectra of both an elliptical (left) and an irregular galaxy (middle) as observed by ALHAMBRA (crosses) and their corresponding best-fit models within a grid generated with the FSPS code (red lines).

**Right:** Mass-to-light ratios in the g band versus k-corrected ($g-r$) colors in the ALHAMBRA low-redshift sample. Even though the stellar population fitting is still preliminary, mass-to-light ratios are consistent with the Bell et al. (2003) parametrization (red line). We have assumed a Salpeter IMF and $h=1$.

Star Clusters in the Tidal Tails of Interacting Galaxies: Photometric Properties and the Tail Environment

Brendan Mullan (Penn State)


We have searched for compact stellar structures within the tidal tails of twelve different interacting galaxies using F606W- and F814W- band images from the Wide Field Planetary Camera 2 (WFPC2) on the Hubble Space Telescope. The sample of seventeen tails of twelve interacting galaxies includes a diverse population of tail lengths, optical brightness, merging mass ratios, HI column densities, and stage on the Toomre sequence. We have found that clustered star formation appears to occur frequently in galaxy interactions, regardless of many gross properties of the interaction and tail environment. However, there is a significant difference in the populations, with some tails having very few luminous clusters. This could be due to certain inhospitable merger dynamics (e.g. high speed, \( V \gtrsim 1000 \text{ km s}^{-1} \) encounters), and/or the timing and strengths of the most recent star formation episodes in the tail. We contend that star cluster formation in tidal tails is likely a ubiquitous consequence of galaxy interactions where there is strong evidence of in situ star formation. Statistical diagnostics also indicate that these clusters arise from initial mass functions similar to those in quiescent galaxies and mergers, but possibly modulated by different peak and exponential parameters related to differences in turbulent pressures and ambient ISM density of the tail environment.

Top: SDSS r-band image of the representative tail NGC 6872E, with HI contours overlaid

Bottom: \( V_{606} \)-band mosaic (left), and \( V_{606} - I_{814} \) map (right). Red circles indicate star cluster candidates within the tidal debris.
The Magellanic Clouds are a local laboratory for understanding the evolution and properties of dwarf irregular galaxies. To reveal the extended structure and interaction history of the Magellanic Clouds we have undertaken a large-scale photometric and spectroscopic study of their stellar periphery (The Magellanic Periphery Survey, MAPS). We present our first results for the Small Magellanic Cloud (SMC); Washington M, T2 + DDO51 photometry reveal metal-poor red giant branch stars in the SMC that extend out to large radii (8.8 kpc), are distributed nearly azimuthally symmetrically (ellipticity=0.1), and are well-fitted by an exponential profile. There is no evidence at ~8 radial scalelengths for a "break" population indicative of a tidal tail or halo. These results suggest that the SMC's major stellar component is either a large, inclined exponential disk or has a large spheroidal structure. The outer stellar distribution contrasts with that of the inner stellar distribution (sometimes referred to as the SMC "bar") that is more elliptical (0.3) and offset from the outer distribution by 0.5 kpc, although they share a similar radial exponential scale length. This suggests that the SMC has an off-center bar as is seen in the LMC. Our enhanced understanding of the stellar structure and populations of the SMC will help shed light on the evolution of dwarf galaxies that are interacting with their larger neighbors.

MAPS fields around the Small Magellanic Cloud. Squares represent CTIO-4m+MOSAIC photometry; shallow photometry in red (V=22) and deep photometry in purple (V=24). The central color image shows the density of red giant branch stars in the combined OGLE-III and MCPS catalogs of the SMC. The black contours indicate the best-fit exponential model to the RGB star density in our MAPS fields out to R=8.4 degrees (e=0.1 and scale-length=1.04 deg). The center of the outer fields is offset by 0.5 degrees from the center of the inner region of the SMC.
Much has changed in the conceptual language of stellar populations in the 30 years since the Hubble Space Telescope was planned, and HST has played a major role in that transformation. I give a brief review of the special contributions made by HST imaging to areas such as the stellar content of globular clusters, hot low-mass populations, the star formation histories of nearby galaxies, extragalactic star clusters, mergers and starbursts, the structural evolution of early-type galaxies, and, of course, our extraordinarily routine access to the high redshift universe.

HST’s last camera, the Wide Field Camera 3, was installed during the May 2009 servicing mission and is optimized for stellar populations research. I describe some of the early studies that have taken advantage of its extended wavelength coverage (0.2-1.7μ), large suite of specialized filters, and improved UV/IR "discovery efficiency." These include the star formation histories of nearby disk and early-type galaxies (from both resolved sources and integrated light), discovery of multi-age pre-main-sequence populations in massive Local Group star clusters, and the evolutionary state of galaxies at intermediate redshifts (z ~ 0.5-3) in the GOODS field.

WFC3 images of a spiral arm field in the Sc galaxy M83 in the near-ultraviolet (F225W filter) and the near-infrared (F814W filter) demonstrating the prominence of the massive star population in the UV despite the presence of large and patchy extinction.
Massive stars are responsible for energetic feedback effects that drive evolutionary processes in star-forming galaxies. Radiative feedback is especially important because it is thought to be responsible for cosmic reionization, as well as ionization of the diffuse, warm ionized medium. Mechanical feedback is responsible for shaping and energizing the interstellar medium, both thermally and kinetically, as well as driving further star formation. Thirdly, chemical feedback is a fundamental process that drives galactic chemical evolution, while also affecting the interstellar energy budget by promoting cooling.

We have a general understanding of how these feedback processes work, and ample qualitative evidence demonstrates their prevalence. I first describe analytic relations to quantify feedback effects, based on simple parameterization of the massive star population. The general framework is broadly consistent with observational constraints.

However, closer investigation of the individual processes reveals that fundamental truths remain elusive. What is the actual importance of mechanical feedback to triggering new generations of star formation? On the one hand, triggering appears ubiquitous; but on the other, its contribution to the stellar mass seems small. What is the energy budget of multi-supernova superbubbles? While it is well-established that individual superbubbles have a growth rate smaller than predicted, we do not know which of the myriad candidate reasons dominate this effect. Are HII regions density-bounded or radiation-bounded? Historically, they have been generally regarded as radiation-bounded, due to broad agreement between predictions and observations of emission-line ratios and nebular luminosities based on stellar content. However, the paradigm lately seems to be shifting toward density-bounding, based on a variety of more detailed studies. On the other hand, when the question is applied to entire galaxies, even starburst galaxies, many studies suggest the opposite: escape fractions of Lyman continuum radiation are small. And what is the nature of the diffuse, warm ionized medium and its radiation transfer? This global ISM component lies at the junction between these opposing paradigms, on different scales, for the fate of ionizing radiation. Its origin and dominant processes remain enigmatic, and clarifying them may be key to reconciling these disjoint pieces into a unified whole.

The feedback effects are closely interrelated and a truly coherent picture has not yet emerged. The fundamental link between the stellar population and feedback processes necessitates integrating our understanding of these to develop a complete picture of galaxy evolution.
Stellar Populations in the Cosmological Context  
STScI May Symposium (2010)

Stellar populations in the super star clusters NGC 3603 and 30 Dor

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Early Release Science observations of the super star clusters NGC 3603 and 30 Doradus in the UV, optical and near IR with the WFC3 show for the first time clear evidence of multiple stellar populations in both clusters with an age spread of 1 to 20-30 Myr. The spatial distributions of the cluster stars indicate that the older population is more widely and uniformly distributed over the cluster field than the much clumpier younger population. A reasonable separation of the main components of these populations can now be made by the use of their Hα excess emission, a good indicator of their pre-main sequence status, allowing a better understanding of the stellar mass function and its evolution in time.

Left: NGC 3603. Dereddened (V, V-I) color-magnitude diagram. Stars showing strong Hα excess emission are plotted as black star points. Most of them (~75%) lie in the canonical pre-main sequence (PMS) region of the CMD (box on right-hand side labeled YPMS). Using PMS isochrones we estimate a median age distribution of 3 Myr. Surprisingly, a number of sources with equally strong Hα emission are located in a bluer region of the CMD (OPMS box) clearly separated by a 10 Myr PMS isochrone (dashed line). This is the first clear signature of the presence of multiple recent stellar generations in NGC3603.

Right: 30 Dor. Density contour plots of the two populations of PMS stars detected in this cluster, also separated by ~10 Myr. The youngest population (thin dotted line) is clearly more centrally concentrated than the older population (thick line), whereas the latter dominates the eastern portion of the field.
Intergalactic Globular Clusters

Eric Peng (Peking University)

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Intracluster stellar populations are a natural result of tidal interactions in galaxy clusters. Measuring these populations is difficult, but important for understanding the assembly of the most massive galaxies. The Coma cluster of galaxies is one of the nearest truly massive galaxy clusters, and is host to a correspondingly large system of globular clusters (GCs). We use imaging from the HST/ACS Coma Cluster Survey to present a definitive detection of a large population of intracluster GCs (IGCs) that fills the Coma cluster core and is not associated with individual galaxies. The GC surface density profile around the central massive elliptical galaxy, NGC 4874, is dominated at large radii by a population of IGCs that extend to the limit of our data ($R<520$ kpc). We estimate that there are $\sim50,000$ IGCs out to this radius, and that they make up $\sim70\%$ of the central GC system, making this the largest GC system in the nearby Universe. Even including the GC systems of other cluster galaxies, we still find that IGCs make up 30-45\% of the GCs in the cluster core.

**Left:** Density distribution of GCs in the central 26'x23' core of the Coma galaxy cluster. Holes in coverage were due to the failure of ACS. Most of the GCs are centered on the central galaxy, NGC 4874, but there is an extended distribution that fills the core of the galaxy cluster, extending to the west toward NGC 4889 and 4908.

**Right:** The radial distribution of GCs in the Coma Cluster core centered on NGC~4874. The surface density of GCs in each bin (black points) is calculated after masking around known galaxies, and statistical subtraction of GCs belonging to these cluster members. The radial profile exhibits an inflection and flattening at large radii, which we interpret as evidence of a large population of IGCs. The dot-dashed line and gray band at bottom denote the surface density of background objects. The dotted line is the modeled radial distribution of GCs belonging to cluster members that are still visible after masking, which are also well below the overall level by a factor of a few. The data are well fit by a Sersic model plus a constant level (solid line). The Sersic component alone is shown as the dashed line.

Multiple Stellar Populations in Star Clusters: the observational scenario

Giampaolo Piotto (Università di Padova)

Co-authors: J. Anderson, R. Bedin, I. King, A. Bellini, A. Marino, A. Milone, S. Villanova, S. Cassisi

For half a century it had been astronomical dogma that a globular cluster (GC) consists of stars born at the same time out of the same material, and this doctrine has borne rich fruits. In recent years, however, discoveries made largely with HST shattered this paradigm, and the study of GC populations has acquired a new life that is now moving it in new directions. By pushing HST to the highest level of photometric and astrometric accuracy, multiple sequences have been identified in the color-magnitude diagrams of several Galactic and Magellanic Cloud GCs where they had never been imagined before. In addition, all GCs with spectroscopic studies show a spread in light-element content, including Na/O and Mg/Al anti-correlations. Multiple populations in GCs are no longer confined to some fascinating objects, but are now widespread.

At the meeting, we will present a summary of the most relevant observational facts regarding multiple generations of stars in star clusters. We will also show most recent results coming from WFC3 which promises to be an exceptionally useful tool to shed light on the phenomenon (see figure below, which is an example of the complexity of the color-magnitude diagram of Omega Centauri disclosed by WFC3 data).

The complexity of star formation scenario, and of the properties of stars in clusters is of more general interest, as it is related to our ability to properly interpret stellar populations in unresolved system.
SED Fitting and High-Z sources: What We Can and Cannot Learn

Nor Pirzkal (STScI)

Co-authors: Steve Finkelstein, Barry Rothberg

We present stellar population fittings to high-z sources using a new Markov Chain Monte Carlo implementation of spectral energy distribution fitting. Unlike methods that rely on finding the best fitting match between observation and models, our method allows us to completely explore the multi-dimensional parameter space of the synthetic models that we use. We show how MCMC allows us to derive the a-priori probability distribution of the stellar ages, stellar masses and extinction using a single or two stellar population models. We have applied our method to high-z objects from GRAPES at 3<5 for which we now have new and deeper NIR WFC3 observations and can compare them to our previous results. We also analyze the SED of z~7 redshift source in the HUDF and show how a more careful estimate of the ages of the stellar population and masses of these objects can now be obtained.

The MCMC method, while somewhat computer intensive allows for a full and complete exploration of the entire parameter space. Unlike more classical methods that rely on finding the best available fit using a pre-determined grid of input model parameters, we are able to determine much more reliable confidence intervals, separately, and for each of the input model parameters.

Based on our experience with using this method, we are finding that stellar masses are often the easiest thing that can be constrained, but that there are cases where even that there is not clear cut solution, as shown below. We also find that we can usually exclude broad ranges of extinction values but that the stellar population ages, and somewhat in contradiction to what has been sometimes claimed in the literature, are significantly more uncertain and can only be determined in a more qualitative manner, and in relation to other input parameters. This is especially true once we allow for more than one stellar population in our models.

**Left:** Single stellar population for to the z~7 object from Labbe et al., 2010.

**Right:** Two population stellar model MCMC fitting of the same object.

Pirzkal et al., 2010, in prep.
Velocity dispersion measurements are presented for several of the most luminous globular clusters (GCs) in NGC 5128 (Centaurus A) derived from high-resolution spectra obtained with the UVES Echelle spectrograph on the 8.2m ESO/Very Large Telescope. The measurements are made utilizing a penalized pixel fitting method that parametrically recovers line-of-sight velocity dispersions (LOSVD). Combining the measured velocity dispersions with surface photometry and structural parameter data from the Hubble Space Telescope enables both dynamical masses and mass-to-light ratios to be derived. The properties of these massive stellar systems are similar to those of both massive GCs contained within the Local Group and nuclear star clusters and ultra-compact dwarf galaxies (UCDs). The fundamental plane relations of these clusters are investigated in order to fill the apparent gap between the relations of Local Group GCs and more massive early-type galaxies. It is found that the properties of these massive stellar systems match those of nuclear clusters in dwarf elliptical galaxies and UCDs better than those of Local Group GCs, and that all objects share similarly old (> 8 Gyr) ages, suggesting a possible link between the formation and evolution of dE,Ns, UCDs and massive GCs. We find a very steep correlation between dynamical mass-to-light ratio and dynamical mass of the form $(M/L)_{\text{dyn}} \propto M^{0.24\pm0.02}$ above $M_{\text{dyn}} \approx 2 \times 10^6 M_\odot$. Formation scenarios are investigated with a chemical abundance analysis using absorption line strengths calibrated to the Lick/IDS index system. The results lend support to two scenarios contained within a single general formation scheme. Old, massive, super-solar [$\alpha$/Fe] systems are formed on short (< 100 Myr) timescales through the merging of single-collapse GCs which themselves are formed within single, giant molecular clouds. More intermediate- and old-aged (~3−10 Gyr), solar- to sub-solar [$\alpha$/Fe] systems are formed on much longer (~Gyr) timescales through the stripping of dE,Ns in the $10^{13}$−$10^{15}$ $M_\odot$ potential wells of massive galaxies and galaxy clusters.

Left: Relations between the dynamical mass $M_{\text{dyn}}$, absolute magnitude $M_V$ and the dynamical mass-to-light ratio $\Upsilon_{\text{dyn}}$ for compact stellar systems and early-type galaxies. 
Right: [$\alpha$/Fe] diagnostic plot. The symbol colors parameterizes the $M_{\text{dyn}}$. We use the population synthesis model predictions from Thomas et al. (2003) for a range of ages, metallicities, and [$\alpha$/Fe] ratios.

For more see: Taylor et al. (2010), ApJ, 712, 1191
The GHOSTS (Galaxy Halos, Outer disks, Substructure, Thick disks and Star clusters) survey is the largest study of the resolved stellar populations in the outskirts of nearby disk galaxies to date. With HST we are studying stars down to 1.5 magnitudes below the tip of the Red Giant Branch both in the disk and in the stellar halo. This allows us to probe stellar densities down to extremely low surface brightness level, equivalent to approximately $32 \, V$-mag arcsecond$^{-2}$.

The survey consists of 14 nearby disk-type galaxies covering a range of masses, inclinations and morphologies. With the ACS and WFC3 instruments onboard HST we target several fields in each system, principally along the major and minor axes to constrain the size and shape of the stellar halos, as well as their structure and composition. For each field we also carry out artificial star tests to assess the completeness and estimate photometric errors.

Data from the survey has already yielded interesting results. For instance, by equating stellar densities to surface brightness, we find that the extended minor-axis profiles of each system correlates with the galaxy’s central bulge (or Hubble type): the larger the bulge-to-disk ratio, the shallower the outer profile. Moreover, both the bulge and the stellar halo of the larger systems can all be fit with one Sérsic profile. However, the profiles appear steeper than theoretical predictions. This could indicate that the true halos only dominate at distances $>30 \, \text{kpc}$, or that the treatment of baryonic matter in the simulations needs to be readdressed.

We have also begun exploring a range of phenomenon such as disk truncations, substructure and the metallicity of the halos. These studies are placing strong constraints on cosmological simulations and furthering our understanding of galaxy formation.

The first data release from the survey will be available soon. However GHOSTS continues to take observations with HST in order to increase the sampling of each galaxy and to push further out into the stellar halos of the systems.
In the early universe, the cosmic star formation rate was high and the formation of massive star clusters was common. Therefore, the study of young massive clusters (YMCs) in local starburst environments plays a crucial role in our understanding of galaxies at high redshifts. In both nearby YMCs and distant galaxies, broadband photometry is commonly used to estimate physical properties such as masses, ages, and extinctions; however, contamination from ionized gas emission is often neglected. By comparing spectroscopic and photometric observations of young massive star clusters to evolutionary synthesis models, we assess the impact of nebular continuum and line emission on broadband photometry of YMCs (Reines et al. 2010). We find that nebular continuum can actually rival the stellar continuum at optical wavelengths and that contamination from line emission is severe in many commonly used broadband filters. Neglecting the effects of nebular emission in observations of YMCs can lead to gross overestimates of stellar masses, older ages, and erroneous extinctions, clouding our understanding of the birth and evolution of massive clusters. Similarly, nebular emission should not be readily dismissed when interpreting observations of starburst galaxies throughout the universe.

Left: Spectrum of an extragalactic young massive star cluster convolved with the HST/ACS F814W (I-band) total system throughput curve. The best-fit model SED is shown as a solid blue line. The stellar and nebular continua are shown as dashed and dotted lines, respectively. The relative contributions of the stellar continuum, nebular continuum and emission lines to the total flux of this filter are approximately 40%, 40%, and 20%. Right: Ratio of the nebular continuum to the total continuum as a function of wavelength for a Starburst99 SSP at various ages. At young ages, nebular continuum is a significant component of the total continuum at optical wavelengths, especially shortward of the Balmer and Paschen jumps located in the U- and I-bands. The impact of emission lines is not included here.

References:
Ancient Stars Dwarf Galaxies Beyond the Local Group

Marina Rejkuba (ESO)

Co-authors: Gary Da Costa, Helmut Jerjen, and Eva Grebel

The brightest unambiguous indicators of the presence of an ancient stellar population (age > 11 Gyr) are the blue horizontal branch stars and RR Lyrae variables. Based on deep HST ACS color-magnitude diagrams for two Sculptor dwarf galaxies ESO 294-010 and ESO 410-005, we show for the first time unambiguous evidence that substantial star formation must have taken place at the earliest cosmological epochs in dwarf galaxies beyond the Local Group. The CMDs of these two galaxies reveal extended horizontal branches that are typically found in ancient globular clusters. The discovery of RR Lyrae variables in both galaxies reinforces our conclusions. The lower density of Sculptor group with respect to our Local Group probes a different environment. These results thus suggest that gas can condense and form stars in low mass halos at the earliest epochs even in relatively low-density dwarfs, providing new constraints to star formation and galaxy formation models at early cosmological epochs.

Left and Center: ACS color-magnitude diagram for ESO 294-010 and ESO 410-005, respectively. The variable star candidates are indicated with large red dots. The majority of them are RR Lyrae variables as revealed by their location on the Horizontal Branch as well as their lightcurves. The lightcurves for a sample of RR Lyrae variables are shown in the right panel.

The discovery of multiple stellar generation now in several among the most massive globular clusters has been one of the most exciting recent achievements with HST. Particularly surprising has been to realize that some of these generations are highly helium enriched. Understanding through which processes successive stellar populations have formed inside such clusters, and how the helium enrichment took place is a very urgent and intriguing issue, with obvious implications for age-dating clusters and stellar populations. Based on the existing empirical evidence, I will constrain as much as possible the scenarios for the origin of these multiple populations. The demands of generating populations that are highly enriched selectively in helium, with little or no concomitant enrichment in heavy elements, has forced all proposed scenarios to very contrived assumptions and solutions. In particular, it appears to be almost inescapable that the progenitors of clusters such as omega Cen and NGC 2808 ought to be 10 to 100 times more massive than these clusters are today, suggesting that the making massive globular clusters may have resulted in major events in the early Universe, perhaps involving $10^8$ - $10^9$ solar masses of gas and making several $10^7$ solar masses of stars.
Bulges are commonly believed to form in the dynamical violence of galaxy collisions and mergers. We have modeled the stellar kinematics data of the Bulge Radial Velocity Assay (BRAVA) and find no sign that the Milky Way contains a classical bulge formed by scrambling pre-existing disks of stars in major mergers. We construct a simple but realistic N-body model of the Galaxy that self-consistently develops a bar, which immediately buckles and thickens in the vertical direction. The projected surface brightness distribution of the model agrees with the 2μm surface brightness distributions observed in various surveys. We use the Bulge Radial Velocity Assay kinematic data (Rich et al. 2007; Howard et al. 2008), a survey of 10,000 M giants with radial velocities measured using Hydra at CTIO. The N-body model fits the BRAVA data with striking agreement and no need for a merger-formed classical bulge component. Our best-fit model has a bar with 4 kpc half-length, and extends 20° from the Sun-Galactic Center line. We use the new kinematic constraints to show that any classical bulge contribution must be <8% of the disk mass. We assert that the Galactic bulge originated from the disk, and is not a separate component made via a prior merger. Massive disk-like galaxies like the Milky Way present a major challenge to the standard picture in which galaxy formation is dominated by hierarchical clustering and galaxy mergers.
Draining the Pond in NGC 6397

R. Michael Rich (UCLA)


In 2005, a 126 orbit ACS integration provided the deepest HST pointing ever on a globular cluster (Richer et al. 2006; 2008) resulting in an age determination from the white dwarf cooling sequence (Hansen et al. 2007). At the time, the only available first epoch imagery was from WFPC2, covering ~60% of the field. We returned in 2010 (GO-11633) to obtain 9 orbits of second epoch ACS imagery at the same position, enabling us to construct a proper motion cleaned color-magnitude diagram for the entire field (see reduction methods in Anderson et al. 2008). By selecting only the stars with the proper motion of NGC 6397, we reveal the complete “blue hook” of the white dwarf cooling sequence, and by plotting those stars in the field population, we are able to identify candidate white dwarfs in the bulge/halo field, behind NGC 6397. Future projects include a determination of the white dwarf cooling ages of M4, NGC 6397, and 47 Tuc, as well as modeling the Galactic halo population. The new CMD is the deepest ever obtained.

Left: The complete color-magnitude diagram would include the field population along the line of sight, and NGC 6397. The clump of objects at F814=27.5, F606-F814=1.4 are candidate white dwarfs in the Galactic halo; some extragalactic objects are present as well, and a very careful rejection of background objects is required (see poster and Rich et al. 2010).

Right: Selecting objects sharing the proper motion of NGC 6397, we reveal the entire white dwarf cooling sequence, including the blue hook (caused by the emergence of H$_2$ molecular opacity). This is the most complete survey of the blue hook phase of WD evolution ever reported.

Richer, H. et al. 2006, Science, 313, 936

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Deep Multi-Color Imaging in 47 Tuc: Some Early Results

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47 Tuc is the nearest (at least in apparent distance modulus) of the bulge/disk globular clusters and is also a template for extragalactic work on resolved stellar populations. Hence its age and stellar content is important in understanding how our galaxy formed and in understanding our nearest resolved galaxies. GO 11677 is an ambitious imaging program with HST to explore these and other facets of this cluster. The program was allocated 121 orbits in cycle 17 and uses both ACS and WFC3. A primary goal is to obtain the white dwarf cooling age of the cluster, compare this with the turnoff age determined with numerous filter combinations and explore for the end of the hydrogen-burning main sequence in both optical and near IR bands. Data collection began in January 2010 and will take almost a full year. In this talk I will present both the preliminary ACS CMD in F606W and F814W and the IR CMD in F110W and F160W obtained with WFC3. The age of the cluster based on these data will be discussed even though it is still extremely preliminary.

An preliminary aperture photometry CMD of 47 Tuc in the near IR filters F110W and F160W. The upper “kink” is the main sequence turnoff (TO) while the lower one is caused by collision induced absorption largely in the H2 molecule (Kink). The spread in the lower main sequence is significantly larger than the photometric errors. The diagonal sequence at faint magnitudes is the upper main sequence and turnoff of the SMC.
An Integral Field Spectroscopic study of the stellar populations in LIRGs and ULIRGs

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Co-authors: Santiago Arribas, Almudena Alonso Herrero, Luis Colina, Ana Monreal Ibero and Macarena García Marin.

We present VIMOS-VLT and PMAS optical integral field spectroscopic observations of a sample of LIRGS and ULIRGs. We generated an atlas of VIMOS continuum, Hα emission flux and Hα equivalent width (Hα-EW) reconstructed maps. The continuum images trace the stellar light while the Hα images mainly trace the ionizing stellar populations. We find that the morphologies of the Hα maps are substantially different than those of the continuum for the majority of the objects in our sample, frequently revealing compact concentrations extending up to few kpc of the nuclear region. In addition, it is found that the concentration of the Hα emission is not correlated with the infrared luminosities (LIR) of the sources, which could be explained in terms of higher concentrations of dust towards the nuclear regions of objects with higher LIR. On the other hand, the PMAS observations are used to investigate the star formation histories of the objects. To this end, we have used a large number of combinations of two stellar populations to fit the optical stellar continuum and the hydrogen recombination lines of selected regions of the galaxies. Adequate fits are obtained for the majority of extracted spectra with models comprising a low reddened, evolved component with typical ages of 0.7-5 Gyr plus an ionizing stellar component with higher extinctions. Since the majority of the objects in our sample are relatively isolated spirals or weakly interacting galaxies, our results are consistent with a scenario by which spiral-like LIRGs have not undergone a major starburst in the last 1-2 Gyr and are constantly forming stars as in the case of normal spirals.

Constraining the Evolution of Virgo Cluster Galaxies with Stellar Populations

Joel Roediger (Queen’s University)

Co-authors: Stéphane Courteau, Michael McDonald, Lauren MacArthur

A critical test of models of galaxy formation and evolution is to reproduce the star formation and chemical evolution histories for galaxies of all types. Towards this end, we have performed detailed stellar population decompositions of a multi-band database of resolved $griH$ photometry for a sample of nearly 300 Virgo cluster galaxies (McDonald et al. 2010). This sample typically achieves an $H$-band surface brightness depth at least one magnitude deeper than 2MASS, encompasses all morphological types and spans a wide range of environmental conditions. Our modeling of colour gradients has yielded systematic trends in the (deep) stellar population gradients, ages and metallicities of these galaxies as a function of morphology, structure and local (galaxy & ICM) density. Some of these trends are weak in light of the significant scatter in the above stellar population diagnostics. However, among the strongest observed trends we note correlations of galaxy ages with neutral gas deficiency (Fig. 1) and of galaxy metallicities with the $H$-band luminosity and surface brightness (Fig. 2). These correlations indicate that more gas-deficient systems are older, while those with a greater stellar mass and deeper gravitational potential are more chemically enriched. Moreover, Hubble type appears to play a non-negligible role in shaping galaxies stellar populations, with earlier-type galaxies being older, more enriched, and having flatter age and metallicity gradients. Decoding these results further in terms of popular formation and/or evolutionary scenarios is challenging, yet a likely interpretation is provided in Roediger et al. (2010).

Fig. 1: (left) Mean age, $<A>_{eff}$, versus surface brightness, $\mu_e$, at one effective radius. The points are shaded according to Hubble type, while the curves show the median trend for early-type (red), spiral (green) and irregular (blue) galaxies. The coefficient $r$ for each trend is provided. (right) As at left but shown versus the HI gas deficiency, $Def_{HI}$, parameter. The curve and $r$ value in this case correspond to all galaxy types.

Fig. 2: As in Fig. 1 but shown for metallicity at one effective radius, $Z_{eff}$, versus (left) apparent magnitude, $H$, and (right) $\mu_e$. The bottom windows show the residuals from linear fits to the above bivariate distributions versus $\mu_e$ (left) and $H$ (right). No trend is observed.
G. Ruchti (JHU), J. Fulbright (JHU), R. F. G. Wyse (JHU), G. Gilmore (IoA, Cambridge), and the RAVE Collaboration

Theories of thick disk formation can be differentiated by measurements of stellar elemental abundances. We have undertaken a study of metal-poor stars selected from the RAVE spectroscopic survey of bright stars to establish whether or not there is a significant population of metal-poor thick-disk stars ([Fe/H] < -1.0) and to measure their elemental abundances. We have obtained spectroscopic data for a large sample of candidate metal-poor thick disk stars stars, which extend to much larger distances (typically 1-2 kpc) than previous studies. We have found confirmed metal-poor stars in the thick disk with metallicities ranging down to [Fe/H] = -1.9, and that have enhanced [α/Fe] ratios (see Figure 1). This enhancement implies that enrichment proceeded by purely core-collapse supernovae. This requires that star formation in each star-forming region had a short duration. The relatively low scatter in the ratios also suggest the ISM was well mixed prior to star formation. Additionally, the metal-poor thick disk and the most α-enhanced halo stars have similar [α/Fe] ratios, evidence that they have had enrichment from a similar massive star IMF. We conclude that the enhancement in [α/Fe] does not support direct accretion of stars from satellite galaxies after redshift z ≤ 1, since stars of similar metallicities in present day dwarf galaxies show lower [α/Fe] ratios.

Figure 1: [α/Fe] versus [Fe/H].
Black Circles = Thin Disk,
Green Diamonds = Thin / Thick Disk, Red Squares = Thick Disk,
Orange Plus Signs = Thick / Halo, Blue Triangles = Halo
Star Formation History in the Small Magellanic Cloud

Elena Sabbi (STScI)

Co-authors: Monica Tosi, Antonella Nota, Jay S. Gallagher, Gary Da Costa, Jay Anderson, Eva Grebel, Michele Cignoni, Katharina Glatt

As the closest late-type star forming dwarf galaxy, the Small Magellanic Cloud (SMC) is an ideal laboratory for detailed studies of these very common objects. Furthermore its proximity allows us to reconstruct its star formation history (SFH) over a Hubble time, by exploring ages, metallicities and spatial distribution of its stellar content. The properties of old (age > 10 Gyr) and intermediate (2 < age < 10 Gyr) stellar population can help us understand the formation and the evolution of the Local Group (LG). In order to get a more accurate and complete evaluation of the SFH of the SMC from the earliest epochs up to the present day we observed six fields in the SMC that sample regions characterized by different stellar and gas densities, and possibly different SFH, in the SMC bar, wing and outskirts. From the comparison of the color-magnitude diagrams (CMDs) with Padova isochrones (Fig. 1) for different metallicities (Bertelli et al. 1994) we found that:

- In the earlier epochs (8 < age < 12) star formation (SF) proceeded at a low speed.
- The SMC formed stars over a long interval of time until ~2-3 Gyr ago, with a possible increase in the star forming activity between 4 and 6 Gyr ago.
- We found evidence for a radial chemical gradient, with the metal poorer stars found in the outskirts, suggesting that the SF activity was significantly lower in the periphery.
- A modest gradient has been detected also in the intermediate and old age star clusters (Glatt et al. 2008), suggesting that in the SMC stars and clusters share similar histories.
- In the last ~800 Myr SF has been more active in the central area, and that a sizable fraction of stars were formed ~400-500 Myr ago.


![Figure 1: CMDs mF814W vs mF555W-mF814W of the six SMC fields, with superimposed Padova isochrones of metallicity Z=0.004 (in blue) and Z=0.001 (in red). Red dotted dashed lines are isochrones of 12 Gyr, continuous red isochrones are for 5 Gyr, and red dashed isochrones are for 3 Gyr old stellar populations. Blue dotted-dashed lines are 500 Myr isochrones, continuous blue isochrones are for 100 Myr, dashed blue isochrones are for 50 Myr, and dotted isochrones are for 10 Myr old stellar populations.](image-url)


Benjamin Sargent (STScI)

Co-authors: Sundar Srinivasan, Margaret Meixner

The Surveying the Agents of a Galaxy's Evolution (SAGE) Spitzer Space Telescope Legacy project has obtained photometric data at mid-infrared wavelengths (3.6, 4.5, 5.8, 8, and 24 microns) for over 6 million stars in the Large Magellanic Cloud. Amongst this sample are thousands of asymptotic giant branch (AGB), red supergiant (RSG) and other evolved stars, which have circumstellar dust shells emitting in these Spitzer bands. Combined with optical and near-infrared photometry from other sources, we have assembled Spectral Energy Distributions (SEDs; emitted flux versus wavelength) for these evolved stars. To determine the dust mass-loss from the oxygen-rich (O-rich) evolved stars, we have constructed a grid of radiative transfer models using 2Dust. Each model assumes mass is lost from the star at a constant rate, and that the resulting dust shell from this mass loss is spherically symmetric. For each model in the grid, the stellar radiation field assumed is a detailed stellar photosphere spectral model. The grid explores different values of stellar effective temperature, stellar luminosity, dust shell inner radius, and dust shell optical depth at 10 microns wavelength. We then seek for each O-rich evolved star candidate from the SAGE sample the best fit of model to data in terms of SED photometry. From this, we obtain best-fit values and their uncertainties for the four parameters mentioned, in addition to dust mass-loss rate (itself output from 2Dust). From the best-fit values of stellar effective temperature and luminosity for each O-rich evolved star, we determine mass and age by assuming stellar evolutionary tracks. We then explore mass-loss in the context of stellar populations in the Large Magellanic Cloud.


Sargent et al., 2010, in prep
Using gamma-ray bursts (GRBs) to investigate galaxy formation and evolution has the advantage that galaxies hosting GRBs are selected because an energetic stellar explosion has happened, and not because of their brightness. A fraction of galaxies are missing from traditional counting due to the small size (although less-massive galaxies are much more numerous than massive galaxies, especially at high redshift) or to a combination of large distances and dust extinction. These galaxies are observationally particularly difficult to find, unless a GRB occurs. Many galaxies hosting GRBs at redshift \( z < 2 \) have high star formation rate and low stellar mass. However, a large fraction of GRBs is dark in the optical (no precise localization and unique identification of the host) due to dust extinction or very high redshift. We propose the idea that some dark-GRB hosts are related to high-\( z \) massive galaxies with very high SFR and dust extinction (e.g., similar to sub-mm galaxies, SMGs). Some observational hints suggest that galaxy mergers are common in the GRB host population, another feature reminiscent of SMGs. Although a key ingredient triggering the GRB event, over the whole cosmic universe, has not been uniquely identified, it seems that high star formation is a common feature in all GRB environments, and not metallicity, as commonly indicated by theoretical models of the GRB progenitor.

\[
\begin{align*}
\rho_* & [M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}] \\
& \times 10^3 \\
& \times 10^0 \\
& \times 10^1 \\
& \times 10^2 \\
& \times 10^3 \\
& \times 10^4 \\
\end{align*}
\]

Fig. 1: The cosmic star-formation rate density (SFRD) as given by the total galaxy population (grey filled dots) and by different classes of galaxies (all other symbols). Measurements from GRB hosts (red diamonds; Kistler et al. 2009) indicate that a large fraction of SFRD is not accounted by traditional galaxy surveys. This might be due to a severe dust extinction of highly star-forming regions in massive galaxies. The lower-redshift counterparts would be sub-mm galaxies at \( z < 3 \) (red filled squares; Michałowski, Hjorth & Watson 2009). (Figure modified from Kistler et al. 2009).
A Comparative Analysis of the Stellar Populations of Galactic and M31 Globular Clusters

Ricardo Schiavon (Gemini Observatory)

Co-authors: Nelson Caldwell, Heather Morrison, Stéphane Courteau, Genevieve Graves, Paul Harding, Lauren MacArthur, James Rose.

We present a comparative analysis of absorption line indices measured in high S/N MMT/Hectospec spectra of 352 M31 globular clusters (GCs) and in the CTIO library of MW GC spectra by Schiavon et al. (2005). Focusing on old clusters, we revise the claim by Burstein et al. (1984, ApJ, 287, 586)---and many others---that CN is stronger in M31 GCs than in their MW counterparts of same metallicity. In fact, we find no evidence for differences between the two cluster samples in any of the absorption line indices measured, indicating an absence of differences between the two cluster families in age or in the abundances of Fe, Mg, C, N, and Ca. We show that the dispersion of Balmer line indices at fixed metallicity in the M31 GC spectra cannot be explained by measurement errors alone. Evidence from line ratios, UV colors, and detailed comparison of spectra of clusters of same metallicity, but different Balmer line strengths, suggests that the Balmer line dispersion is due to variations in horizontal branch morphology, at fixed metallicity---in other words, to second parameter effects in M31 GCs. We show that second parameter effects are present in M31 GCs at metallicities as high as $[\text{Fe/H}] = -0.4$. We find tentative evidence that the spatial distribution of metal-rich clusters with blue horizontal branches tends to be more concentrated than that of the rest of the M31 cluster family.

Left: Lick indices measured in M31 (gray) and MW GCs. No difference is found between the two cluster families in any of the indices measured. Old MW and M31 GCs seem to have similar ages and abundance patterns. In particular, we find no evidence for CN enhancement in M31 GCs. The dispersion of Balmer line indices in M31 clusters is real, and seems to be cause by variations in horizontal branch (HB) morphology in M31 GCs, at fixed $[\text{Fe/H}]$ (second parameter effects). Evidence for blue HBs is found in M31 GCs with $[\text{Fe/H}]$ as high as $\sim -0.4$. Right: Difference between $H\gamma$-strong and $H\gamma$-weak mean M31 GC spectra (gray), compared with the residuals between metal-rich MW GCs with blue and red HBs. Note the similarity between the two spectra, and in particular the presence of high order Balmer lines, typical of A-type blue HB stars.
Cold Halo Substructure and Milky Way Formation

The accretion history of the Milky Way is partially encoded in its halo substructure. I describe the results of a systematic statistical search for elements of cold halo substructure (ECHOS) in the radial velocity distribution of stars in the inner halo of the Milky Way observed during the Sloan Extension for Galactic Understanding and Exploration (SEGUE) survey. Radial velocity substructure is systematically older than surface brightness substructure (e.g., tidal streams), and therefore provides a direct measure of the accretion history of the Milky Way in a region and time interval that has yet to be fully explored. I measure average chemical abundance properties in ECHOS and in the kinematically smooth population along the same line of sight and I use that information to better determine the characteristics of their progenitors. I find that ECHOS are unlikely to be disrupted globular clusters or ultrafaint dwarf spheroidal (dSph) galaxies, and there is evidence to suggest they are the debris of a $M_{\text{tot}} \sim 10^9$ solar mass dSph galaxy or galaxies.

Figure 1. A comparison of the metallicity of ECHOS to the metallicity of the metal-poor main sequence turnoff (MPMSTO) population in the kinematically smooth component of the inner halo along the same line of sight where the ECHOS was discovered. Left: ECHOS are more iron-rich than the MPMSTO stars associated with the kinematically smooth inner halo. The mass-luminosity relation of Milky Way dSph galaxies requires a progenitor luminosity $L \sim 10^8 L_{\odot}$ to reach a mean iron metallicity $[\text{Fe/H}] \sim -1.0$, ruling out ultrafaint dSph galaxies. Right: ECHOS are less $\alpha$-enhanced than the MPMSTO stars associated with the kinematically smooth inner halo, so (modulo any changes in the initial mass function) the MPMSTO stars in ECHOS formed in environments in which the star formation timescale was long relative to the star formation timescale in the massive progenitor of the bulk of the inner halo. For that reason, ECHOS are unlikely to be formed by the tidal disruption of globular clusters. In general, this abundance pattern is characteristic of massive dSph galaxies.
The Star Formation History of the Leo I Dwarf Spheroidal Galaxy

Tammy Smecker-Hane (Univ. of California, Irvine)
Co-authors: Brian Marsteller, Andrew Cole, John Gallagher, James Bullock

We used the Hubble Space Telescope (HST) Advance Camera for Surveys (ACS) to deeply image a field in the Leo I dwarf spheroidal galaxy (dSph) to derive its star formation history over the last 14 Gyr by modeling the observed density of stars in the observed color-magnitude diagrams (CMD) using the latest Padova stellar evolutionary models (Marigo, et al. 2008). Approximately 50% of the Leo I dSph's stars formed over 9 Gyr ago, but star formation continued in it until only a few $10^8$ years ago. Thus we find Leo I is much older than previously thought (Gallart, et al. 1999, Dolphin 2002). It began forming stars vigorously at the same time all the other Local Group galaxies began to form stars. Our new imaging goes much fainter than previous data, allowing us to unambiguously identify the main sequence turnoffs of the ancient population and constrain the star formation rate at the epoch of the formation of the "first stars" in this galaxy. In addition, the chemical abundance distribution we derived from CMD analysis agrees extremely well that the one we derived independently by measuring chemical abundances from spectra of its red giant stars (Bosler, et al. 2007). Like other dSphs, Leo I has a very highly peaked metallicity distribution, which argues for infall of pristine gas over time and the outflow of metal enriched winds playing a significant role in its evolution (see, for example, Lanfranchi & Matteucci 2007).

Left: The observed CMD of the Leo I dSph created from our ACS images. Solid lines show example of theoretical isochrones from Marigo et al. (2008). Note the prominence of stars at the main-sequence turnoff for ages > 10 Gyr, and the obvious structure in the MSTO region signifying changes in the SFR.
Right: The derived Star Formation Rate (Top) as a function of age for the Leo I dSph galaxy. The present time is age = 0 Gyr.

The 6dFGS Fundamental Plane

Christopher Springob (Anglo-Australian Observatory)

Co-authors: Matthew Colless, Heath Jones, Christina Magoulas, Jeremy Mould, Rob Proctor, Lachlan Campbell, John Lucey, and the 6dFGS team

The 6dF Galaxy Survey (6dFGS) is an all southern sky galaxy survey, including 125,000 redshifts and more than 10,000 peculiar velocities, making it the largest peculiar velocity sample to date. In combination with 2MASS surface brightnesses and effective radii, 6dFGS yields the near-infrared Fundamental Plane (FP) for a large and uniform sample. We have fit the FP relation for the galaxies in the peculiar velocity sample using a maximum likelihood method (Colless et al. 2001 MNRAS 321, 277, Saglia et al. 2001 MNRAS 324, 389) which allows us to precisely account for selection effects and observational errors.

We have derived stellar population parameters for the galaxies in the peculiar velocity sample, as in Proctor et al. (2008 MNRAS 386, 1781). We have investigated the effects of varying stellar populations and environments on the FP, and find clear trends of stellar population parameters across and through the FP. In contrast to the results of Graves, Faber, & Schiavon (2009 ApJ 698, 1590), we find that the stellar population parameters vary with log(R_e) and log(I_e) when other Fundamental Plane parameters are held constant. Indeed, we find that the stellar population parameter variation depends most strongly on a galaxy's position along the axes of the 3-d gaussian we use to describe the Fundamental Plane. Age varies through the plane. [Mg/H] varies across the plane in the shorter of the two principle axes of the 3-d gaussian within the plane. [Mg/Fe] and [Fe/H] is an intermediate case. None of the stellar population parameters show any variation along the longest axis of the 3-d gaussian.

There are two possible ways to use the stellar population trends to reduce the scatter in the FP and derive better distances and peculiar velocities. One is to use the stellar population models to make adjustments to the surface brightnesses, correcting them to a fiducial value of one or more of the stellar population parameters. The other is to bin the galaxies by stellar population parameters, and make the correction to fiducial values of the stellar population parameters along the direction in FP space imposed by the partial derivatives. We will explore each of these options in future work.

Above: Galaxies are binned by their position in Fundamental Plane space. In each bin, we calculate the median value of log(age) (left) and [Mg/H] (right). Bins are then represented by spheres, color coded by the median value of the respective parameter, such that the redder colors have higher values of the respective stellar population parameter. The radius of each sphere is proportional to the number of galaxies in the bin. The log(age) plot on the left is an edge-on view of the Fundamental Plane, and one can see a clear variation of age through the plane. The [Mg/H] plot on the right is a face-on view, and one can see a clear variation of [Mg/H] across the plane.
I review our current understanding of the star formation process. I focus on the birth of massive stars, star clusters, the initial mass function, and the connection to kiloparsec and galactic-scale star formation laws.

Some open questions to be addressed are:

What controls the rate and clustering of star formation in GMCs?
What sets the stellar initial mass function and binary properties, and do these vary with environment?
How does massive star formation differ from low-mass star formation?
What is the timescale of star cluster formation?
What is the lifetime of GMCs?
What sets the initial cluster mass function and does this vary with environment?
What sets the rate and efficiency of kpc-scale star formation in different environments?
How does global galactic star formation activity vary with gas content, orbital shear, amplitude of spiral density waves, pressure, metallicity, and feedback environment?
What processes influenced the cosmic evolution of star formation?

A more extensive discussion of these questions than I will be able to present in a single talk can be found in the presentations made at the recent From Stars to Galaxies conference, available at http://conference.astro.ufl.edu/STARSTOGALAXIES/
Modeling the stellar populations of high-redshift galaxies: Is what you see what you get?

Scott C. Trager (Kapteyn Astronomical Institute, Groningen, NL)

Co-authors: R.S. Somerville, M. Arrigoni

I briefly review the properties of stellar populations of nearby galaxies to show what parameters we can determine with high signal-to-noise spectra. I proceed to show how we interpret these parameters using mock catalogues based on recent semi-analytic models that include full galactic chemical evolution. I then briefly review the "zoo" of high-redshift galaxies (dropouts, DRGs, BzKs, etc.) and review attempts to understand the star formation histories of these objects, in particular dropouts, from broad-band photometry. I show our own attempts to understand the star formation histories of DRGs. I conclude with pointing directions forward in this effort, some of which is already coming with WFC3 grism spectroscopy, and some of which will have to wait until JWST and the era of the 30—40 m telescopes.

Arrigoni et al. 2010b, in prep.
Stellar Populations in the Cosmological Context
STScI May Symposium (2010)

Extragalactic Star Clusters in Intermediate-Age
Galaxy Merger Remnants

Gelys Trancho (Gemini Observatory)

Co-authors: Bryan W. Miller, Daniel Burnett, David Palamara and Francois Schweizer

Gemini Observatory, University of Adelaide, Monash University, Carnegie Observatories

We present preliminary results of combining HST optical photometry with ground-based K-band photometry from NIRI and Flamingos-I on Gemini to study the star cluster systems of four intermediate-age merger remnants (NGC 2865, NGC 1700, NGC 7727 and NGC 4382). The galaxies were chosen based on blue colors and fine structure such as shells and ripples that are indicative of past interactions. We find evidence for intermediate-age star clusters with ages consistent with the estimated merger ages.

Left: $X^2$ test result for NGC 2865, NGC 1700, NGC 7727 and NGC 4382. The different levels represent the reduced $X^2$ of the comparison between the age distributions in the observed systems using SSP models. Right: V-I vs V-Ks diagram for NGC 4382. Model grids are from SSP models. Bottom: Merger remnants ages calculated in this work versus other authors.

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<th>Modeled age (Gyr)</th>
<th>Published age (Gyr)</th>
<th>Reference</th>
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<td>3±1</td>
<td>Brown et al 2000</td>
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<td>NGC7727</td>
<td>0.9±0.5</td>
<td>~1</td>
<td>Crabtree et al 1994</td>
</tr>
</tbody>
</table>

References:
1. Schweizer & Seitzer (1992)
2. Whitmore et al. (1997)
3. Schweizer (private communication)
5. Trancho et al. (2004)
7. Bruzual & Charlot 2007 (private communications)
Stellar Populations in the Cosmological Context
STScI May Symposium (2010)

Gemini Spectroscopic Survey of Young Star Clusters in Merging/Interacting Galaxies: Stephan's Quintet

Gelys Trancho (Gemini Observatory)

Co-authors: Nate Bastian (School of Physics, University of Exeter), Iraklis S. Konstantopoulos (Pennsylvania State University), Sarah C. Gallagher (University of Western Ontario) and Jane S. Charlton (Pennsylvania State University)

The goal of the Gemini Spectroscopic Survey of Young Star Clusters in Merging/Interacting Galaxies is to use clusters as tracers of the evolution of their host galaxies. Using optical spectroscopy we have derived the ages and metallicities of dozens of massive clusters in nearby ongoing mergers. While spectroscopy is much more expensive than photometry in terms of telescope time, it allows for precise (non-degenerate) age/metallicity derivations and also offers the advantage of kinematical information that can be used to identify sub-populations within the merger/interaction.

Thus far, we have focused on ongoing major mergers between spiral galaxies, namely NGC 3256 and the Antennae galaxies. For the Antennae, we compared our results, and those of Whitmore, on the age distribution of the cluster to numerical models of the galaxy merger and found evidence for an increasing star-formation history over the past few hundred Myr. Additionally, we found clusters in the (projected) outer disks of the participating spiral galaxies that have "halo" type kinematics, showing the randomization of stellar orbits and the formation of a stellar halo around the future merger remnant. In the current study, we shift our focus to the much more complicated environment: Stephan’s Quintet, a compact group of interacting galaxies. In particular, we concentrate on the clusters that populate the intra-group medium (IGM; mostly in tidal structures), with the aim of using the clusters’ ages and kinematics to constrain the dynamical history of the interactions.

Left: Gemini/HST images of Stephan’s Quintet. The observed clusters are shown where red represents clusters, which display an absorption dominated spectrum, while green represents emission dominated spectra. Right: Determination of ages and metallicities of the clusters. Hγ vs. [MgFe] from the Gonzalez-Delgado, 2005 SSP models for four different metallicities are shown.

References:
1. Trancho et al. 2007a
2. Trancho et al. 2007b
4. Whitmore et al. 2007
A number of spectroscopic and photometric observations have shown that many globular clusters host multiple stellar populations and challenged the common paradigm that globular clusters are ‘simple stellar populations’ composed of stars of uniform age and chemical composition.

I will present the results of a study of the formation and dynamical evolution of multiple stellar populations in globular clusters based on an extensive set of hydrodynamical and N-body simulations. I will show results concerning the initial structural properties of second generation stars and the dependence of the amount of second generation stars formed on a cluster’s initial properties. I will then show how the structure, the relative number of first and second generation stars and their spatial distributions evolve during a cluster early and long-term dynamical evolution.

Finally, I will present the results of an investigation aimed at calculating the fraction of the mass of the Galactic stellar halo composed of globular cluster second-generation stars and illustrate the connection between the current properties of multiple populations in globular clusters, their origin and dynamical evolution and the formation history of the Galactic halo.
A major scientific question still being explored is how star-formation has evolved in galaxies at redshifts higher than \( z=1 \)? How did these earlier galaxies assemble into today’s Hubble sequence? In order to answer these questions we have constructed the number counts of far-UV (FUV) galaxies as a function of magnitude which provide a direct statistical measure of the density and evolution of star-forming galaxies. We report on the results of measurements of the rest-frame FUV (\( \lambda_{\text{obs}} \approx 1500\text{Å} \)) number counts computed from data of several fields including the HUDF, the HDF-N, and the GOODS-N and -S fields. These data were obtained from the Hubble Space Telescope Solar Blind Channel Camera of the Advance Camera for Surveys and cover more area and more lines of sight than previous studies. The number counts cover an AB magnitude range from 20-29 magnitudes and probe galaxies at \( z < 1 \). We compare our number counts with local FUV counts from GALEX (Xu et al. 2004, Hammer et al. 2010) and the latest semi-analytical models (Somerville et al. 2008, Gilmore et al. 2009). During this decade, the infrared observational capabilities of JWST will allow us to probe even deeper into the assembly history of star forming galaxies. As you look towards higher redshifts, the rest-frame UV band-shifts into the infrared, making this spectral region a primary target for detecting the earliest star-forming galaxies. The future work of our current project is to determine morphologies and other characteristics of the FUV sources in our number counts sample which would be valuable to compare with future JWST observations of higher-z sources.

Left: FUV number counts of field galaxies compared with previous FUV number counts from various fields of view. In general, our data agree with the semi-analytical models, perhaps with a slight preference for the WMAP5 model. Only the faint end of our counts agree with the SB4/Lya-flat SED model. At AB=22.5 our counts connect well with the faint end of the bright Coma field GALEX counts.

Right: In the table magnitudes represent the centers of bins and errors are Poissonian from Gehrels (1986). At AB > 29, small \( \frac{1}{4} \) magnitude bins were used to accommodate the sharp drop-off in survey sensitivity over most the area.

ABSTRACT

The morphology of H-Alpha emission has been used to age-date star clusters in the nearby grand-design spiral galaxy M83, based on our new WFC3 observations. The basic premise is that the distribution of H-alpha is largely coincident with the distribution of optical light in the youngest clusters (i.e., < few Myr), is in a small ring-like structure around the optical cluster in slightly older clusters where stellar winds from the cluster have had time to blow a bubble (i.e., 5 Myr), and is in a larger ring-like bubble for still older clusters (i.e., 5 - 10 Myr). If no H_alpha is associated with the cluster the age is greater than 10 Myr.

Summary

1. H-Alpha morphology can be used to age-date clusters.
2. A tentative classification system has been developed to map a proposed sequence of cluster evolution onto the observed morphology.
3. A comparison of visually estimated H-Alpha categories with ages determined using Spectral Energy Distributions (SEDs) based on UBVH-Alpha observations shows agreement at the ~90 % level, with rms ~0.2 dex for young and ~0.5 dex for older clusters.
It is not yet clear whether the star formation in circumnuclear starbursts occurs in a single burst, or whether it is due to the propagation of star formation from one region to another. The high precision age-dating possible from UV spectra of young (a few Myr old) star clusters provides a means of differentiating between these two scenarios. We analyze archival HST/STIS FUV imaging and spectroscopy of compact star clusters within a few x100 pc of the optical nucleus of M83 (NGC 5236, 4.6 Mpc). M83 hosts the nearest example of a circumnuclear starburst in a barred spiral galaxy, and it is nearly face-on. We compare the observed spectra with two sets of Starburst99 models, semi-empirical models based on an empirical library of Galactic stars (Robert et al. 1993), and fully theoretical models based on a synthetic library of high-resolution UV spectra for hot massive stars (Leitherer et al. 2010). We generate single stellar population models at various ages, and we then use the model that best fits the data for determining the intrinsic reddenings, ages, and masses of the brightest clusters in M83’s starburst. We compare the above properties with those derived from HST/WFC3 optical photometry. The latter is more sensitive to the masses than the UV spectroscopy because i) it captures light from stars in a lower mass regime, and ii) the total light can be better estimated from the photometry. We find no evidence for triggered star formation.

Left: HST/STIS FUV spectroscopy (black curves) and best model fits (grey curves). For clusters 1, 2, 3, 4, and 6, we show models based on the empirical (left) and theoretical (right) stellar libraries.

Right: Ages from HST/WFC3 photometry for clusters 1-13.

References: Wofford et al. 2010, in prep.
Connecting the Dual Origin of Simulated Halos with Observable Trends in Stellar Populations

Adi Zolotov (New York University) ; Co-authors: Beth Willman, Alyson Brooks, Fabio Governato, David W. Hogg, Shijing Shen, James Wadsley

Four fully cosmological, high-resolution N-Body + Smooth Particle Hydrodynamic simulations are used to investigate the chemical abundance trends of stars in simulated stellar halos as function of their origin. These simulations include a self-consistent treatment of all the major physical processes involved in galaxy formation, including a physically motivated supernova feedback recipe, metal enrichment, metal cooling, and metal diffusion. These simulations allow us to study the competing importance of in situ star formation and accretion of stars from satellites in the building of stellar halos. While the outer regions of these galactic halos were assembled through pure accretion, the inner regions (r<30 kpc) of all four halos contain both accreted stars and stars formed in situ (see Figure 1 for the relative contribution of each population to the halo of MW1, one of our simulated galaxies).

Most of the in situ halo stars formed at high redshift out of smoothly accreted cold gas in the inner ~4 kpc of the galaxies’ potential wells, possibly as part of their primordial disks. These stars were then displaced from their central locations into halo orbits through a succession of mergers. The relative contribution of the in situ population to each stellar halo was found to be a function of a galaxy’s merging history, and ranges between ~ 10 and 30 %. A galaxy with recent mergers, like M31, may host relatively fewer in situ stars in its halo then a galaxy with a more quiescent merger history, like the Milky Way.

We have also analyzed the abundance pattern ([Fe/H] vs [O/Fe]) of all halo stars located within 10 kpc of a solar-like observer. In galaxies which have not experienced a recent major merger, high metallicity in situ stars (shown in red triangles in Figure 2) are found to be more alpha rich than accreted stars (shown in black circles) at similar metallicities. This dichotomy in the [O/Fe] of halo stars at a given metallicity results from the different potential wells within which in situ and accreted stars form. It may thus be possible for observers to use such trends in stellar populations to uncover the relative contribution of different physical processes to the Milky Way’s halo formation.
