Star Formation Histories of Local Galaxies

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Acknowledgements

Some of the research presented herein is my own done with...

postdoctoral researcher Brian Marsteller (UCI),
my former graduate students Tammy Bosler, and my colleagues
Andrew Cole (U. Tasmania),
Jay Gallagher (U. Wisconsin-Madison),
James Bullock (UCI), Peter Stetson & James Hesser (HIA/DAO)

And much of the research has been done by other groups, too.

If you are interested in this topic, a good way to learn more is to read this recent review paper: Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group, Tolstoy, Hill & Tosi (2009, ARAA)
...All These Facilities Are Needed

Happy 50th Year!
1. Local Group Galaxies
2. Using Color-Magnitude Diagrams to Derive Star Formation Histories of Galaxies
   a) Stellar Evolution/CMDs
   b) Techniques for Deriving SFHs
   c) Examples: Carina & Leo I dSph, SMC/LMC, M31
4. Chemical Abundances
5. Implications for Galaxy Formation
   a) Despite having very small velocity dispersions (~15 to 20 km/s), most dSphs have formed stars over many Gyr. Some only ran out of gas in the past 1 Gyr.
   b) Despite actively forming stars over most of the Hubble time, the stars in dwarfs have nearly a constant metallicity. The galaxies enrich quickly to an [Fe/H] that correlates well with the galaxy’s total luminosity. This implies dwarfs (dSphs & dIrrs) must accrete fresh gas over time and have metal-enriched winds.
The Inner Regions of the Local Group*

* Sphere around M Way with r < 1 Mpc
Local Group as a Laboratory

Contains galaxies covering a very wide range mass, luminosity and gas:star ratios

- Milky Way/M31 \( L_V \approx 2 \times 10^{10} L_V \odot \)
- LMC \( L_V \approx 2 \times 10^9 L_V \odot \)
- Fornax dSph \( L_V \approx 2 \times 10^7 L_V \odot \)
- Carina dSph \( L_V \approx 3 \times 10^5 L_V \odot \)
- Ultra Faint dSphs \( L_V \approx 3 \times 10^3 L_V \odot \)
Hierarchical Formation of Galaxies

ΛCDM N-body simulation (dark matter only) of the evolution of a Milky Way type galaxy from Bullock & Johnston (2005)
Hierarchical Formation of Galaxies

ΛCDM N-body simulation (dark matter only) of the evolution of a Milky Way type galaxy from Bullock & Johnston (2005)
Stellar Populations of Galaxies

Collisions of proto-galactic fragments early in the evolution of a galaxy causes dissipation of energy & funnelling of gas into the center, which may create bursts of star formation & form a galactic bulge.

Stellar halos maybe be created from early merging of the proto-galactic fragments and later from cannibalization of dwarf galaxy satellites.

Dwarf galaxies, being the simplest systems, should be excellent laboratories in which we can determine the important physics (inflow, outflow, etc.) of galaxy evolution.
Differences Between Galaxy Types and Star Clusters

Central Surface Brightness

\[ \mu_v \text{ (mag arcsec}^{-2}) \]

\[ M_v \]

Tolstoy, Hill & Tosi 2009
• Dekel & Silk (1986) using a simple analytical model predicted outflows dominate evoln if $v < 100 \text{ km/s} \rightarrow Z \propto L^{0.4}$, but at least one of their key assumptions is very wrong. More work is needed.

• Scaling Relationships tell us that star formation is probably not controlled mostly by environment, but by the physics of star/galaxy formation itself.
Galaxy Formation
Galaxy Formation

Star Formation
(Gas $\rightarrow$ Stars)
Galaxy Formation

Star Formation

(Gas $\rightarrow$ Stars)
Galaxy Formation

Star Formation
(Gas $\rightarrow$ Stars)

Evolution of Mass
(DM + Gas) of Galaxies:
Infall of DM + Gas & Gas Outflow in Galactic Winds
Galaxy Formation

Star Formation
(Gas $\rightarrow$ Stars)

Evolution of Mass
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← CMDs
Galaxy Formation

Star Formation
(Gas $\rightarrow$ Stars)

Evolution of Mass
(DM + Gas)
of Galaxies:
Infall of DM + Gas &
Gas Outflow in
Galactic Winds

$\leftarrow$ CMDs

$\leftarrow$ Chemical Abundances of Stars
Stellar Evolution in the HR Diagram

• Massive Stars evolve and change $T_{\text{eff}}$ at fixed $L$ → Supergiants

• Low Mass Stars evolve and change in both $T_{\text{eff}}$ and $L$ → Red Giant/AGB stars

• $\tau_{\text{MS}} = 10 \text{ Gyr} \times (M/M_\odot)^{-2.5}$
Main Sequence Lifetimes

- **Main sequence lifetimes:**
  - $M = 10 \, M_{\odot}$, $\tau_{MS} = 32$ million yr
  - $M = 0.5 \, M_{\odot}$, $\tau_{MS} = 56 \, \text{Gyr} > \text{age of the Universe!}$

- All low mass stars with $M < 0.8 \, M_{\odot}$ that ever formed in a galaxy are still there

- Measuring the # stars at different parts of the HR Diagram can tell you a galaxy’s star formation history

- **Hess Diagram:** diagram showing the density of stars in bins of color & magnitude in an HR Diagram
Star Clusters

As the cluster ages, the main-sequence turnoff degreases in mass, becoming redder and fainter.

Shape of the CMD tells you the age, distance and chemical abundance of the cluster.
Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)
Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)

Main Sequence (unevolved stars)
Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)

MSTO (sensitive to age)

Main Sequence (unevolved stars)
Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)

Horizontal Branch Stars (core He burning)

MSTO (sensitive to age)

Main Sequence (unevolved stars)
Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)

Horizontal Branch Stars (core He burning)

MSTO (sensitive to age)

Main Sequence (unevolved stars)

Red Giant Branch
Globular Cluster M30

- Isochrones from Vandenberg et al. (1997)

- Comparing the observed fiducial points to the theoretical isochrone allows you to determine the cluster’s reddening, distance, & age (chemical composition)
Stellar Evolutionary Models

• Padova Isochrones (Girardi et al. 2000)

• An Illustration of How Metallicity and Age affect an Isochrone
Stellar Evolutionary Models

• Padova Isochrones (Girardi et al. 2000)

• An Illustration of the Age-Metallicity Degeneracy of the Red Giant Branch
The Carina dSph Galaxy

- Initial work by Mighell (1990) suggested a complex SFH
- Results from the CTIO 1.5 m Telescope over a wide field (Smecker-Hane, et al. 1994)
The Carina dSph Galaxy

Deeper Photometry from the CTIO 4 m Telescope
(Smecker-Hane, et al 1996; see also Mighell 1990,
Hurley-Keller et al. 1996)
What are the Differences Between Dwarf Spheroidal & Dwarf Irregular Galaxies?

Leo I
Dwarf Spheroidal galaxy (dSph)

Leo A
Dwarf Irregular Galaxy (dlrr)
What are the Differences Between Dwarf Spheroidals & Dwarf Irregulars?

<table>
<thead>
<tr>
<th>Leo I dSph:</th>
<th>Leo A dIrr:</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ $M_V = -11.7$</td>
<td>▪ $M_V = -11.9$</td>
</tr>
<tr>
<td>▪ Devoid of neutral gas, $M_{\text{HI}} &lt; 10^3 M_\odot$</td>
<td>▪ Plenty of neutral gas, $M_{\text{HI}} = 2 \times 10^7 M_\odot$</td>
</tr>
<tr>
<td>▪ No star formation in last ~0.5 Gyr, but Gallart et al. (1999) &amp; Dolphin (2002) suggested a majority young stellar pop</td>
<td>▪ Current star formation &amp; HII regions $\Psi(t_{\text{now}}) \approx 10^{-4} M_\odot/\text{yr}$</td>
</tr>
<tr>
<td>▪ Stars: $[\text{Fe/H}] \approx -1.4$</td>
<td>▪ Stars: $[\text{Fe/H}] \approx -1.4$</td>
</tr>
<tr>
<td>▪ Dark Matter (stellar velocity dispersion)</td>
<td>▪ Dark Matter (HI)</td>
</tr>
</tbody>
</table>
Measuring the Star Formation History (SFH) of a Galaxy

- By modeling the Hess Diagram, the density of stars in the HR Diagram ($T_{\text{eff}}$-L plane) or its observational equivalent, the Color-Magnitude Diagram (CMD) we can derive a galaxy’s SFH.

- Major complications:
  - Degeneracy of age and chemical abundance
  - Uncertainties exist in stellar evolution models and the transformation to the observational plane.

- Other minor complications:
  - Distance along the line-of-sight to the galaxy, differential reddening, photometric binaries, etc.
Where Do We Get the Data?
Where Do We Get the Data?

- Hubble Space Telescope is needed to get accurate CMDs for galaxies $> 100$ kpc, because you need to do high precision photometry on faint stars and sometimes in very crowded regions.
Where Do We Get the Data?

- Hubble Space Telescope is needed to get accurate CMDs for galaxies > 100 kpc, because you need to do high precision photometry on faint stars and sometimes in very crowded regions.

- Major complications:
  - It's difficult to get time on HST!
  - Observing strategy (which filters to use, which texp, how many fields) is based on the efficiency and FOV of the camera.
Analysis of CMDs to derive SFHs

- Gallart, Apparicio, Bertelli, Vallenari and collaborators
  - Use wide boxes in the CMD
  - Match Hess diagram using Chi-Squared analysis
  - Less sensitive to errors in stellar evoln models

  - Use small bins in the CMD
  - Match Hess diagram using Maximum Likelihood Analysis
  - More sensitive to errors in stellar evoln models, but more stringent limits on the solution
Analysis of CMDs to derive SFHs

- Hernandez, Gilmore, & Valls-Gabaud (2000) and Dolphin (2002), etc.
  - Solve for both chemical evolution, $Z(t)$, and $SFR(t)$

- LCID Collaboration deriving SFHs for numerous dwarf galaxies and other groups working on individual dwarfs
The Observed CMD overplotted with selected isochrones (Marigo et al. 2008) with different ages (in Gyr) & metallicities.
SFH of the Leo I dSph Derived From the CMD
Smecker-Hane, et al. (2010)

- The Observed CMD overplotted with selected Padova isochrones (Marigo et al. 2008) with different ages & metallicities (same as in previous slide)
SFH of the Leo I dSph Derived From the CMD

Smecker-Hane, et al. (2010)

a) Observed CMD
b) Hess Diagram of Observed CMD
c) Hess Diagram of Best Fit Model’s CMD
d) Hess Diagram of Residuals
SFH of the Leo I dSph Derived From the CMD

Smecker-Hane, et al. (2010)
50% of the stars that formed now have ages < 10 Gyr & were formed in the first 4 Gyr after the Big Bang.
Leo A – Dwarf Irregular Galaxy
(Cole, et al. 2007)

Isochrones
Age = 5 & 14 Gyr
Comparing the Leo I dSph & Leo A dIrr

Leo A dIrr (Cole et al. 2007)

Different SFHs for Leo I dSph & Leo A dwarf irregular! Leo I started with big burst of SF, but Leo A started slowly. However both started forming stars ~14 Gyr ago.
Results of SFHs of Dwarf Galaxies

Tolstoy, Hill & Tosi 2009

Results from the LCID Collaboration

Tolstoy, Hill & Tosi 2009
This Raises Some Questions

- All galaxies examined so far began forming stars at about the same time, ~14 Gyr ago, with no sign of pause due to reionization (12.6 Gyr, $z \approx 6$), but each has a seemingly unique star formation history extending over many Gyr. Why? Differences in DM halo masses, differences in continued infall, tidal forces, stripping?

- Do the SFHs derived match those predicted by $\Lambda$CMD? Let's compare with simulations.

- What can we do to further constrain the rate of inflow of pristine gas and outflow of metal-enriched winds? Measure chemical abundances for individual red giant stars in the dSphs. Also, determine abundances for numerous elements that are created on different timescales.
The Calcium Triplet as an Abundance Indicator

A High–Dispersion Echelle Spectrum of an RGB star near two of the CaT lines
(T. Bosler, Ph. D. thesis)
Carina dSph RGB star

$V = 17.9$ mag

Night Sky
Age – Metallicity Relationship in the Leo I dSph Derived From the CMD

Smecker-Hane, et al. (2010)

Comparing such data to analytical models of chemical evolution suggest that in order to get such a flat age-metallicity relationship you need both inflow of fresh gas and outflow of metal-enriched winds (c.f., Lanfranchi, Matteucci & Cescutti 2006)
Metallicity Distribution of Stars in Leo I dSph

Smecker-Hane, et al. (2010)

The results from spectroscopy of individual RGB stars and the new CMD analysis agree beautifully!
Large and Small Magellanic Clouds
The SMC

HST survey of star clusters and field stars in the Small Magellanic Cloud done by a large collaboration: Gallagher, Grebel, Nota, Tosi, Sabbi, Glatt, etc.

Goals:

• Accurately measure the ages (±0.5 Gyr) and distances of star clusters in the SMC
• Use the star clusters to trace the evolution of the metallicity over time in this dwarf galaxy
• Use the field stars to derive the star formation and metal enrichment history
• Identify how cluster formation compares to the star formation
NGC 121: the SMC’s Only Globular Cluster

Glatt, et al. (2008)

5 isochrones displayed at 0.5 Gyr intervals

Age = 10.5 ± 0.5 Gyr
SMC Star Clusters

NGC 121 has an age of 10.5 Gyr and [Fe/H] = −1.46 (“intermediate” metallicity)
NGC 121 is the only globular cluster in the SMC, and is its oldest star cluster

SMC’s current star formation rate is higher than similar galaxies (interaction LMC/SMC)

Is the SMC a “young” galaxy? ... SMC Field Stars say “No.”
The Stellar Populations of the SMC

6 SMC “Field Star” Areas in Gallagher et al.
The Stellar Populations of the SMC

Field Stars in 6 SMC Locations

(Sabbi, et al. 2009)

$Z = 0.004$
Ages = 50, 100, & 500 Myr

$Z = 0.001$
Ages = 3, 5, & 12 Gyr
The Stellar Populations of the SMC

Full analysis of the CMDs is not complete yet, but simply from comparing the CMDs to isochrones, we find that the SMC does have 10-12 Gyr old stars. Just not that many. Thus the SMC had a slow start to its formation… which maybe a reason so few globular clusters formed in it.
Large Magellanic Cloud

- Smecker-Hane, Cole, Gallagher & Stetson (2002) imaged star fields in the LMC with the WFPC2 on the Hubble Space Telescope (HST)

- Derived SFHs for the Bar and Disk 1 fields from the # stars as a function of magnitude on the main-sequence

- 5% of WFPC2 area shown at right; mean separation of stars with $V \leq 25$ mag is $\sim 6$ pix = 0.6"
Black = Larger # stars in the Bar Field
White = Larger # stars in the Disk 1 Field
LMC Field Stars

Bar: Open Histogram
Disk 1: Hatched Histogram

Bar Formation
Figure 11. Total SFH of the LMC, computed by summing over all 1376 regions covering the MCPS survey region. The time axis is shown with a linear scale that is broken into three segments: the left panel covers ~100 Myr, the middle panel covers ~1 Gyr, and the right panel covers ~14 Gyr. The best-fit SFR as a function of age is shown with a thick black line; the uncertainty on the fit (including covariance between age bins) is shown as a gray shaded envelope. The distribution of metallicity at each age is shown by the mix of colors below the SFR line (Z = 0.001 in blue and downward sloping; Z = 0.0025 in green and upward sloping; Z = 0.004 in orange and vertical; Z = 0.008 in red and horizontal).

Figure 20. Age–metallicity relation for the LMC. The points with errorbars are 85 LMC star clusters which have age and metallicity measurements in the literature. The mean metallicity as a function of age derived from our SFH analysis is shown as a heavy line, and its statistical variance is shown as a gray envelope. Our analysis contains only a single value for ages older than 4 Gyr, because we anchored the old SFH to published results based on deep HST imaging.
The LMC

- SFR of the LMC Disk was nearly constant with time, not varying by more than a factor of 2 to 3 (Olsen 1999, Holtzman et al. 1999, Smecker-Hane et al. 2002, Harris & Zaritsky 2009)

- SFH of the LMC Bar is very different than the Disk
  - Initial formation of the bar ~ 4 to 6 Gyr ago, exact age depends on the assumed metallicity
  - SFR in last 1 to 2 Gyr also has been high in Bar

- The LMC, like the Leo I dSph, has a very flat age-metallicity relationship & highly-peaked metallicity distribution, implying continual gas accretion & outflow.
Chemical Evoln Modeling of dSphs

From Lanfranchi, Matteucci & Cescutti (2006), “Detailed Evolution of Carina and Sagittarius dSph Galaxies” ...

and high galactic wind efficiency in both cases. In fact, the galactic winds play a crucial role in the evolution of these galaxies. They develop when the thermal energy of the gas equates its binding energy (see for example Matteucci & Tornambé 1987). This quantity is strongly influenced by assumptions concerning the presence and distribution of dark matter (Matteucci 1992). A diffuse ($R_e/R_d = 0.1$, where $R_e$ is the effective radius of the galaxy and $R_d$ is the radius of the dark matter core) but massive ($M_{dark}/M_{Lum} = 10$) dark halo has been assumed for each galaxy. This particular configuration allows the development of a galactic wind in these small systems without destroying them.

The model allows one to follow in detail the evolution of the abundances of several chemical elements, starting from the matter reprocessed by the stars and restored into the interstellar medium (ISM) by stellar winds and type II and Ia supernova explosions.

The main assumptions of the model are:

- one zone with instantaneous and complete mixing of gas inside this zone;
- no instantaneous recycling approximation, i.e. the stellar lifetimes are taken into account;
- the evolution of several chemical elements (H, D, He, C, N, O, Mg, Si, S, Ca, Fe, Ba and Eu) is followed in detail;
- the nucleosynthesis prescriptions include the yields of Nomoto et al. (1997) for type Ia supernovae, Woosley & Weaver (1995) (with the corrections suggested by François et al. 2004) for massive stars ($M > 10 M_\odot$), van den Hoek & Groenewegen (1997) for intermediate mass stars (IMS) and for Ba and Eu the ones described in LMC05 and Cescutti et al. (2006).

The basic equations of chemical evolution are the same as described in LM03 and LM04 (see also Tinsley 1980; Matteucci 1996), as are the prescriptions for the SF (which follow a Schmidt law – Schmidt 1963), initial mass function (IMF – Salpeter 1955), infall and galactic winds. The type Ia SN progenitors are assumed to be white dwarfs in binary systems according to the formalism originally developed by Greggio & Renzini (1983) and Matteucci & Greggio (1986). The main parameters adopted for the model of each galaxy, together with the predicted time for the occurrence of a galactic wind, $t_{GW}$, can be seen in Table 1.
Chem Evoln Modeling of Ursa Minor dSph

Cescutti & Matteucci (2008, priv. comm.)

- SF ends after ~ 4 Gyr
- Requires both inflow of pristine gas and outflow of metal-enriched winds

![Graph showing Inflow Rate and Outflow Rate vs. Log (Gyr) with function \( \Psi(t) \)]
Chemical Evoln models from Cescutti & Matteucci (2008, priv. comm.)

• Designed to reproduce the observed phot metallicity distribution

\[ \Psi(t) = \nu \, M_{\text{gas}}(t) \]

\[ M_{\text{outflow}}(t) = w \, \Psi(t) \]

• Best Fit for \( \nu = 0.2 \text{ Gyr}^{-1} \) and \( w = 10 \)
Chemical Evolution

- A flat age-metallicity relationship (or very peaked metallicity distribution) often implies both inflow and outflow is needed, i.e., Leo I dSph, LMC, SMC.

- BUT ... in order to solve the “Missing Satellite Problem” cosmologists assume most of the reservoir of gas that could accrete onto dwarfs over time is “boiled off” during reionization. If so, then where do dSphs accrete pristine gas to sustain their star formation over most of the Hubble time?
Another New Frontier in dSph Research: High Dispersion Spectroscopy

- Today large telescopes allow us to get high dispersion spectra of stars in Local Group galaxies
  - Keck 10m + HIRES (single star; multiple orders)
  - VLT + fiber-fed UVES (multiple stars; single order)

- What can you learn?
  - Numerous chemical abundances
  - Because different elements are produced on different timescales, element ratios in stars give you powerful constraints on inflow/outflow of gas from the galaxy
    - $\alpha$ elements (Type II SNe/explode quickly)
    - Fe-peak elements (Type Ia SNe/explode over long timescales)
    - s-process elements (AGB stars/medium? slow?)
    - r-process elements (SNe/quickly)
HIERES Spectra of 2 Sagittarius dSph Stars
(Smecker-Hane & McWilliam 2005)
### Appendix 4

**Periodic Table of the Elements**

<table>
<thead>
<tr>
<th>1</th>
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</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>Li</td>
<td>Be</td>
<td>B</td>
<td>C</td>
<td>N</td>
<td>O</td>
<td>F</td>
<td>Ne</td>
<td>Na</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
</tr>
<tr>
<td>1.008</td>
<td>4.003</td>
<td>6.941</td>
<td>9.012</td>
<td>10.81</td>
<td>12.01</td>
<td>14.01</td>
<td>16.00</td>
<td>19.00</td>
<td>20.18</td>
<td>22.99</td>
<td>24.31</td>
<td>26.98</td>
<td>28.09</td>
<td>30.97</td>
<td>32.07</td>
<td>35.45</td>
<td></td>
</tr>
</tbody>
</table>

#### Dominant Alpha Elements
- Fe Peak Elements

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The 1–18 group designation has been recommended by the International Union of Pure and Applied Chemistry (IUPAC) but is not yet in wide use. No names have been assigned for elements 110–112 and 114. Elements 113 and 115–118 have not yet been synthesized.
Galactic Star Clusters vs Field Stars

Open and Globular Clusters: • Bosler (2004)
Supernovae Nucleosynthesis

- **Type II SNe:**
  - Core collapse of a massive ($\geq 6 \, M_\odot$) star
  - Intermediate mass elements ejected $10^7 - \text{few } 10^8 \, \text{yr}$ after stars form
  - $\alpha$ elements: O, Mg, Si, S, Ca, Ti
  - Yields: $[\alpha/\text{Fe}] = +0.35 \quad [\text{Na/Fe}] = 0 \quad [\text{Al/Fe}] = 0$
    
    (e.g., McWilliam 1997; Woosley, Timmes & Weaver 1993)

- **Type Ia SNe:**
  - Accretion induced collapse of a white dwarf ($M_{\text{WD}} > 1.4 \, M_\odot$)
  - Fe-peak elements ejected $\geq 0.1 \, \text{Gyr} - \text{many Gyr}$ after stars form
  - Yields: $[\alpha/\text{Fe}] = -0.36 \quad [\text{Na/Fe}] = -4.0 \quad [\text{Al/Fe}] = -1.8$
    
    (Thielemann, Nomoto & Yokoi 1986)
Chem Evoln Modeling of Ursa Minor dSph

Cescuti & Matteucci (2008, priv. comm.)

Assumptions: $\Psi(t) = \nu \text{Mgas}(t)$ & $\text{Moutflow}(t) = \omega \Psi(t)$

$\nu = 0.07$, 0.2 and 0.7 Gyr$^{-1}$
What about $\alpha$/Fe in other dSphs & the Milky Way?

Tolstoy, Hill & Tosi (2009)

Trend w/ galaxy luminosity

Trend inside individual galaxies
Brown et al. used HST to image numerous fields in M3 in a series of papers from 2003 – 2009.
M31: The Andromeda Galaxy

Brown et al. (2008)

M31 “Halo” Results:

- The 11 kpc field is contaminated with stars from M31’s extended outer disk
- Halo of M31 @ 21 and 35 kpc is mostly old, but has an age spread and a wide range of metallicity
Conclusions

1. Star Formation Histories
   SFHs derived from CMDs tell us how galaxies convert their gas into stars; SFHs vary widely in Local Group galaxies, but all began forming stars shortly after the Big Bang and many galaxies have only recently run out of gas.

2. Chemical Abundance Distributions of Stars in dSphs
   CaT spectroscopy & CMD analysis can yield information on the metallicity distribution of stars; most galaxies seem to have flat age-metallicity relationships implying infall of pristine gas over long times and outflow of metal-enriched winds.

3. Chemical Evolution of dSphs
   Measuring the evolution of numerous chemical elements with echelle spectroscopy can teach us much about the physics regulating galaxy evolution (inflow/outflow of gas).
Thanks for your Attention ... Any Questions?
Stellar Populations of Galaxies

Questions:

Do all galaxies have stellar halos?

What about a bulge-less spiral like M33?

Do the ages and metallicities of the stars in the halos match the predictions of sophisticated hierarchical galaxy formation simulations, and can they be tested over a range of galaxy luminosity?
M33 Spectroscopic Survey

• With Michael Hood, Matt Teig, Annette Ferguson & Mike Irwin, and myself

• Spectra taken w/ Keck II 10-m telescope and the DEep Imaging Multi-Object Spectrograph (DEIMOS)
The areas studied in different parts of this project DEIMOS spectroscopic fields are the long & narrow fields.
M33 Spectroscopic Survey

• Dispersion = 0.47 Å/pix, Resolution = 1.8 Å

• Exposure time = 3 hrs

• Average S/N per pixel = 6 (3.5 to 15)

• Average Velocity Error = 9 km/s

• Field of View over which slits are placed is 16.3’ x 5.0’

• Multiplexing is key to getting to our eventual goal: observing ∼ 400 M33 RGB stars
M33 Spectroscopic Survey

- Initial runs selected stars for spectroscopy based on Ferguson et al.’s photometric survey (Ferguson et al. 2006)

- Judge whether or not M33 or Milky Way stars after the fact using our DDO51 photometry

- Kinematic results presented here for 173 stars which are likely M33 members based on DDO51 photometry and relative densities of stars in the Hess diagrams of the “cleaned” MWay and M33 CMDs
Spectra of the Calcium Lines

3 Calcium Absorption Lines:
- Wavelength → star’s velocity along the line of sight
- Depth → abundance of Calcium in the star (Ca/H)
Heliocentric Velocity vs Position Angle

Major Axis PA = 22 deg

Secure Giants
Probable Giants
Thin Disk Intrinsic

$\sigma = 15$ km/s

67% w/ dispersion of 18 km/s

33% w/ dispersion of 48 km/s
The Stellar Halo of M33

Omitting Rotating Disk Stars (|Δv| < 35 km/s), what is the intrinsic dispersion in heliocentric velocity?

N = 34 stars

Simple Calculation:
<V_{helio}> = −170 km/s
RMS implies a Halo intrinsic σ = 72 km/s
M33 Star Clusters

- M33 does have a population of star clusters that have much higher velocity dispersion than the HI disk (Chandar et al. 2002)
  - Clusters with age > 1 Gyr have $\sigma = 68$ km/s
  - However only 18 clusters have kinematics that are inconsistent with disk rotation
Globular Clusters

Two different clusters with about the same age, but very different chemical abundances (×25)

M30: [Fe/H] = –2.1

47Tuc: [Fe/H] = –0.7
The Fornax dSph Galaxy
The Fornax dSph Galaxy

Deeper Photometry from the CTIO 4 m Telescope
(Smecker-Hane, et al)