Constraints on Galaxy Evolution from Chemical Abundances, Kinematics & Ages of Stars in Local Group Dwarf Galaxies

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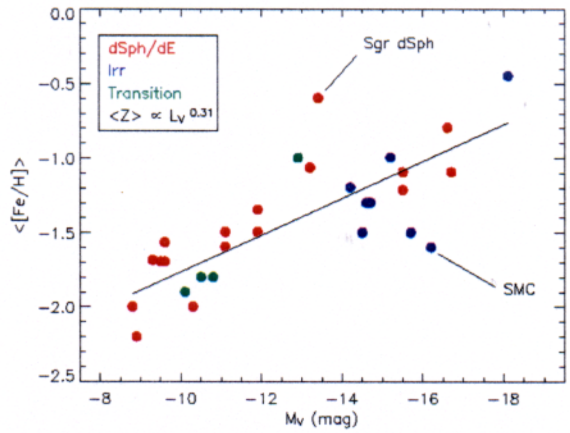
Motivation

- Color-Magnitude Diagrams (CMDs) and Spectroscopy of Resolved Stars in Local Group galaxies can yield extremely accurate information on their
  - Star Formation History
  - Chemical Evolution (inflow/outflow of gas)
  - Kinematic Evolution (dissipation)

- The Local Group contains a wide range of galaxy mass and luminosity:
  - 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 $L_V \approx 1 \times 10^{7} L_{V\odot}$
  - Carina dSph $L_V \approx 3 \times 10^{5} L_{V\odot}$



- Evolution is primarily dominated by processes internal to the galaxy (infall, SF, feedback, outflow) not its environment.
- Dekel & Silk (1986) using a simple analytical model predicted outflows dominate evoln if v < 100 km/s and $Z \propto L^{0.4}$, but at least one of their key assumptions is wrong, and more work is needed.

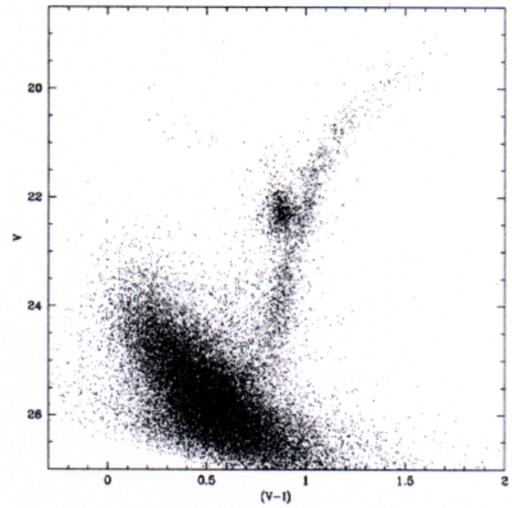
Outline

- Local Group Dwarf Galaxies:
  - Star Formation Histories
  - Chemical abundances derived from Ca II triplet in Carina and Fornax dSphs
  - Chemical abundances, kinematics and ages derived from Ca II triplet in the LMC
  - Evolution of [Fe/H] and Element Ratios in the Sgr dSph
- Conclusion: Surprisingly complex evolution seen for even the lowest mass dSphs!

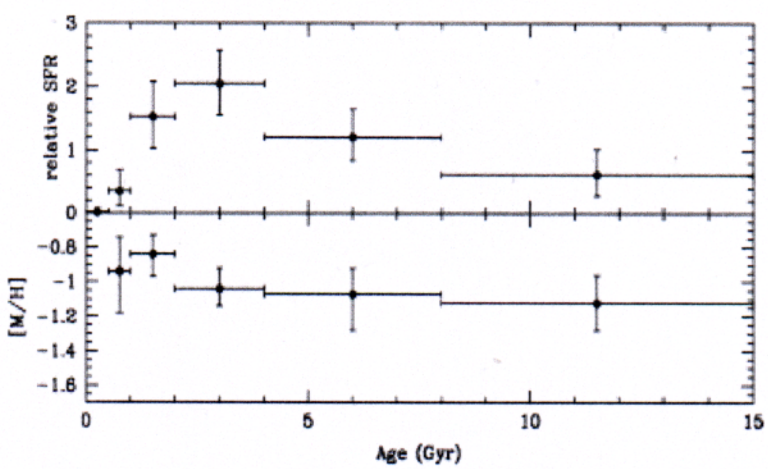
Dolphin (2002): A homogenous analysis of HST WFPC2 CMDs for numerous dSphs

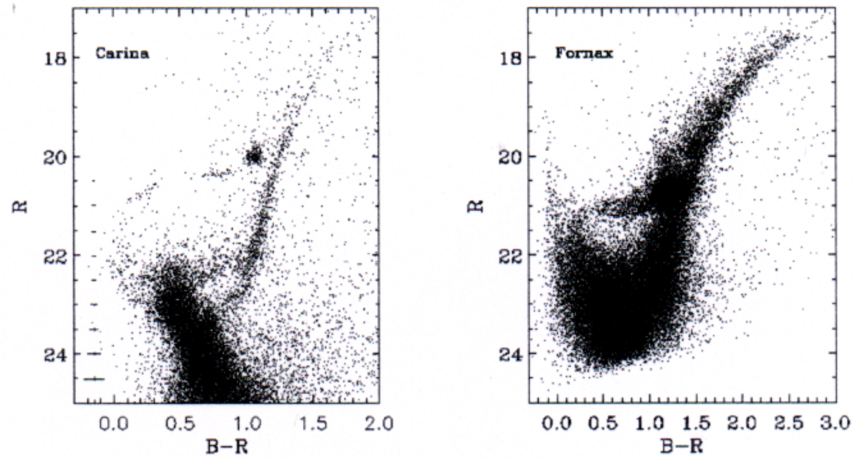
Leo I dSph

Surprisingly young stellar population, but with ancient, ~ 15 Gyr old, stars

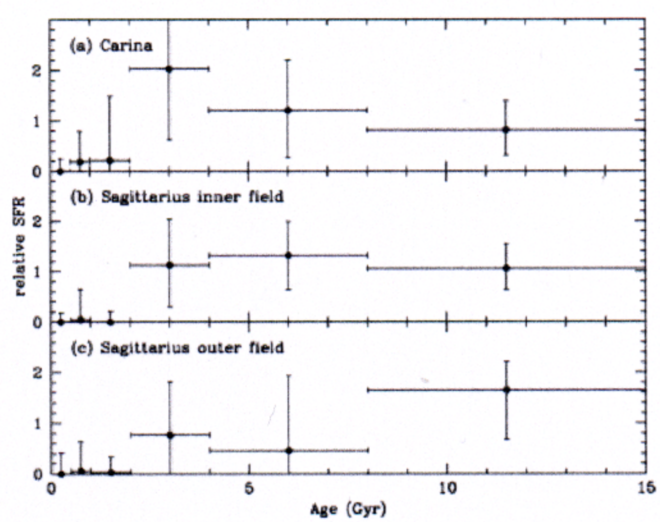


Dolphin (2002): Leo I dSph

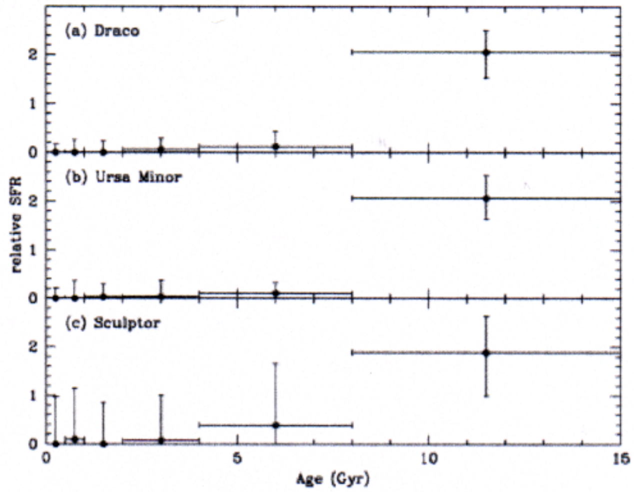




Dolphin (2002)

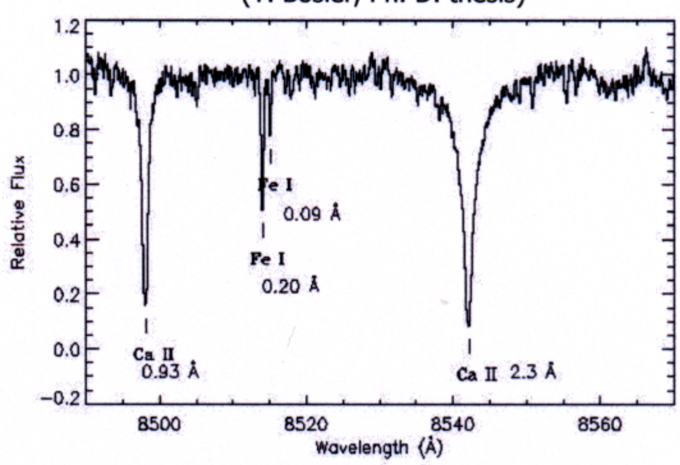


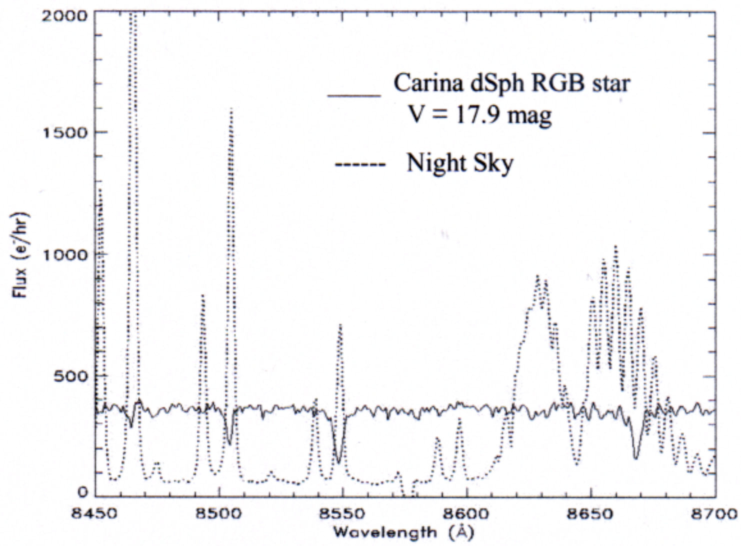
Dolphin (2002)



SF occured over *many* Gyr in most dSphs.
How can we constrain the inflow/outflow of gas from dSphs?
By deriving the chemical evolution & SFH

(T. Bosler, Ph. D. thesis)





Measured with the Argus Multifiber Spectrograph on the CTIO 4m Telescope (Smecker-Hane, Mandushev, et al. 2003)

Ca II Triplet

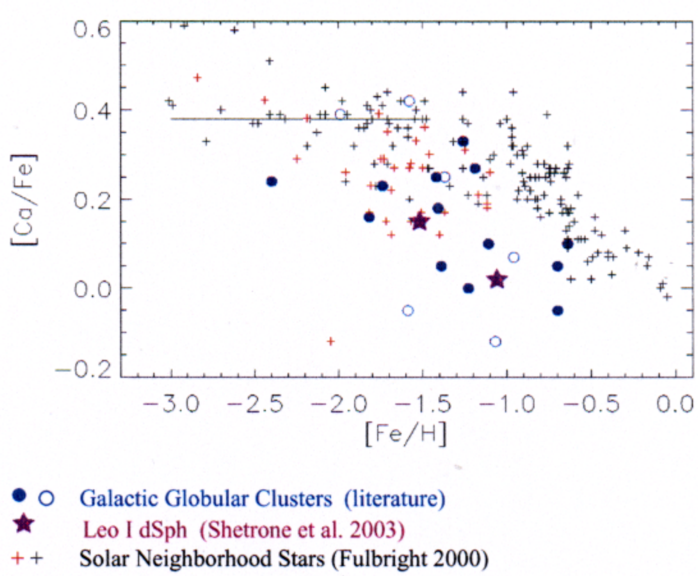
Advantages:

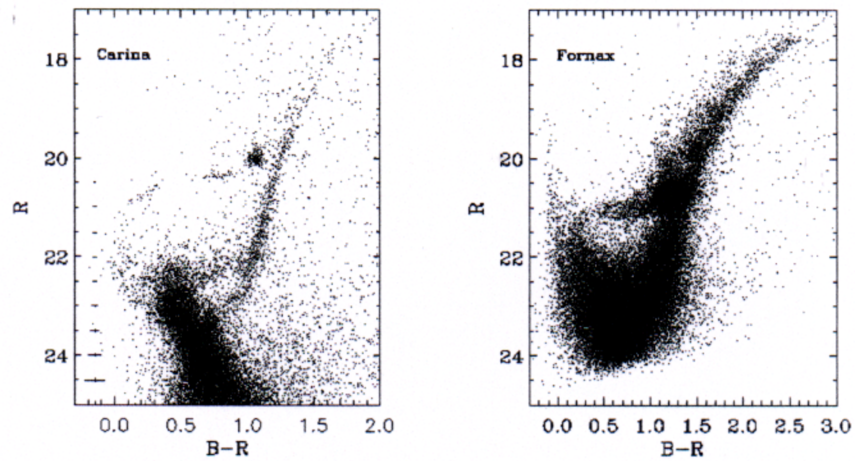
- "Reduced Equivalent Width", $W' = \Sigma W + 0.64\,(V - V_{HB})$, is simply related to metallicity, $[Fe/H]_{CG97} = -2.66 + 0.41\,W'$
- Empirically calibrated by Rutledge et al. (1997a, 1997b) using 19 GCs with [Fe/H] derived from high-dispersion spectra (Carretta & Gratton 1997)
- Only S/N ≈ 30 at R=2500 required for random errors of 0.1 dex in [Fe/H]
- Samples of *hundreds* of stars can be obtained with multiobject spectrographs

Ca II Triplet

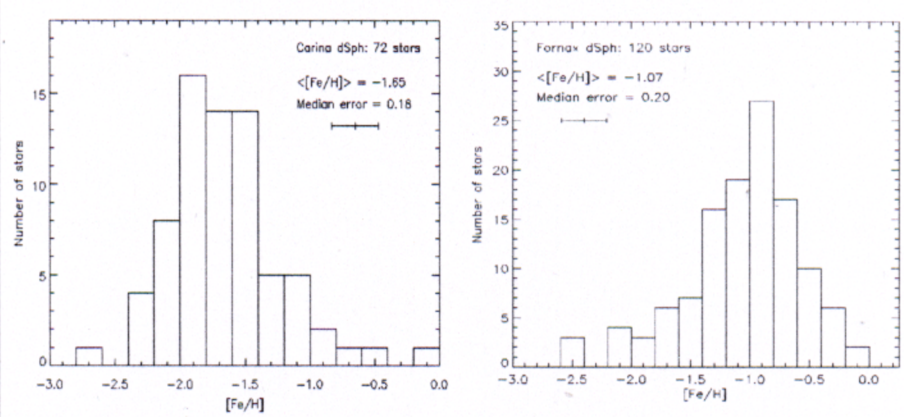
Drawbacks:

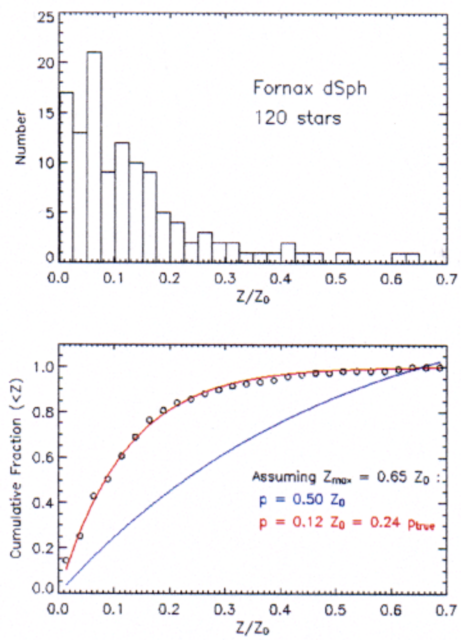
- Present calibration assumes Galactic chemical evolution, i.e., [Ca/Fe] – [Fe/H] relationship
- Not calibrated for ages < 14 Gyr, nor high metallicities
- A new calibration of W ′ → [Ca/H] is being done by T. Bosler (Ph. D. thesis, 2004) to overcome these drawbacks and to remove systematic errors when using it in external galaxies whose chemical evolution is different than the Galaxy.





Smecker-Hane, Mandushev, et al. (2003, in preparation)





Simple Chemical Evolution Models:

- Closed Box with a yield, $p = 0.24\ p_{true}$, much lower than the "standard" yield.
- Simple Outflow Model, where mass loss rate $\propto c\ \psi(t)$:

$$p_{eff} = p_{true}/f$$
$$c = \alpha\,(f - 1)$$
$$c = 2.5 \text{ for } \alpha = 0.8$$

- Simple Outflow Model:

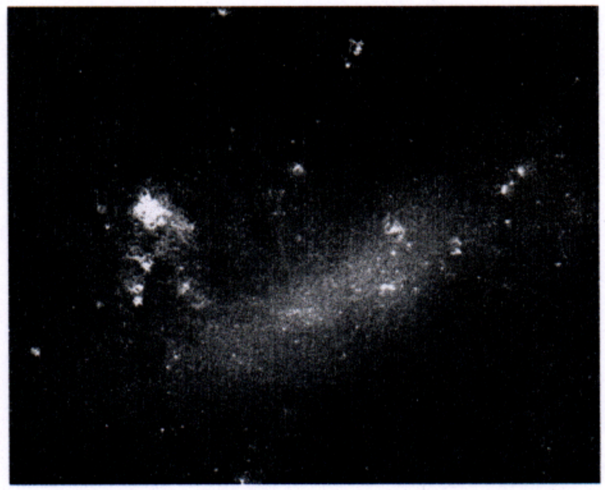
mass loss rate $\propto c\ \psi(t)$

$$p_{eff} = p_{true}/f$$
$$c = \alpha\,(f - 1)$$
$$\alpha = 0.8$$

- Fornax dSph MDF:
  $f = 4.1$
  $c = 2.5$
- MW Globular Cluster MDF (Hartwick 1976):
  $f = 13$
  $c = 10$
- Conclusion: The proto-galactic fragments in which the GCs formed were much "leakier" boxes than a satellite as massive as the Fornax dSph.

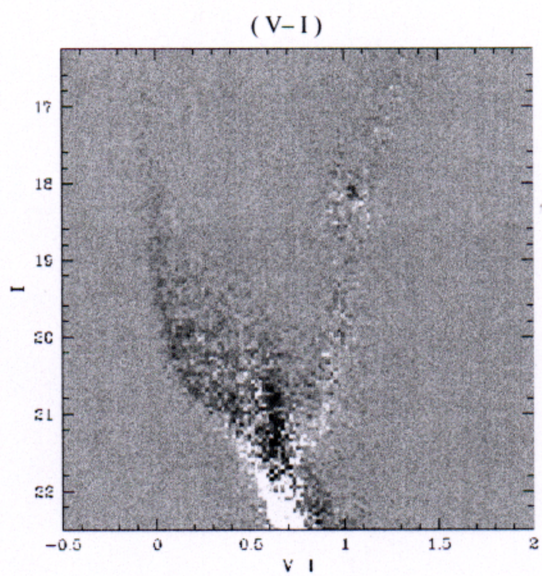
The Large Magellanic Cloud

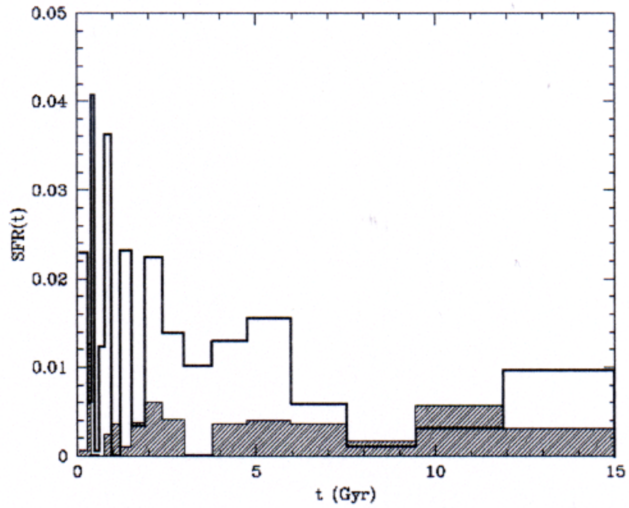
- "Dwarf " Irregular
  $M_V = -18.1$
  $L_V = 0.1\ L_{MW}$
- Stellar bar, thin disk, flattened halo/thick disk
- Currently, SF scattered in knots across the disk



@ NOAO/AURA/NSF

Differential Hess Diagram (Black=Bar; White=Disk)





Open = LMC Bar Hashed = LMC Disk 1

Results on the LMC SFH

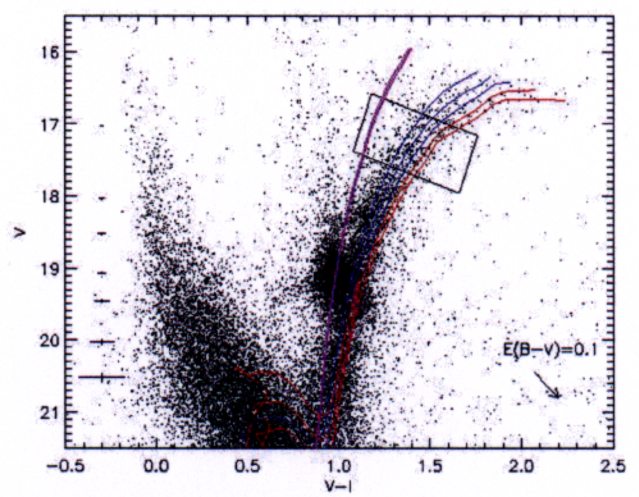
Smecker-Hane, Cole, Gallagher & Stetson (2002)

- SFR of the LMC Disk field was nearly constant with time, not varying by more than a factor of 2, in the last $\approx$ 1 to 15 Gyr.
- SFH of the LMC Bar is very different from that of the Disk
  - Initial formation of the bar $\approx$ 4 to 6 Gyr ago, depending on metallicity.
  - SFR in last 1 to 2 Gyr also has been high.

- We note a distinct lack of metal-poor stars in both fields, but *not* a lack of old stars.
- Independently constrain the metallicity distribution through spectroscopy of individual red giants to increase the accuracy and uniquenesss of our derived SFH.

Chemical Abundances, Kinematics and Ages for RGB Stars in the LMC Disk

- Initial results for 39 stars in Disk 1 from single-slit spectra at Ca II triplet obtained w/ CTIO 4-m telescope (Cole, Smecker-Hane & Gallagher 2000)
- Results for 264 stars in Disk 1 and Disk 2 from spectra obtained w/ Hydra at CTIO 4-m telescope (Smecker-Hane, Cole, Mandushev, Bosler & Gallagher 2003)
  - $\sigma_{[Fe/H]}$ = 0.1 dex (random) and $\sigma_{[Fe/H]}$ = 0.18 (total)
  - radial velocities with errors ≈ 5 km/s
  - ages with errors ≈ factor of 2

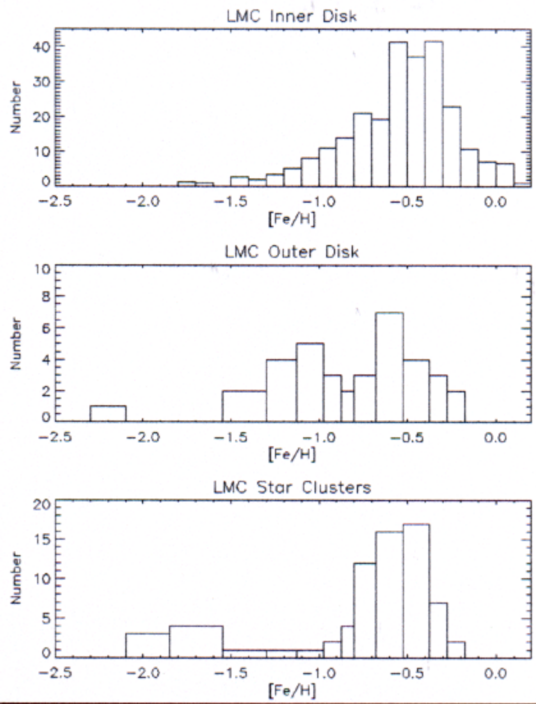


Padova Isochrones (Girardi et al. 2000):
[Fe/H] = −1.7, Ages= 12, 14, 16 Gyr
[Fe/H] = −0.7, Ages = 3, 5, 7 Gyr
[Fe/H] = 0.0, ages= 2, 2.5, 3 Gyr

Smecker-Hane et al. (2003); r = 2 kpc

Olszewski (1993); r = 8 kpc

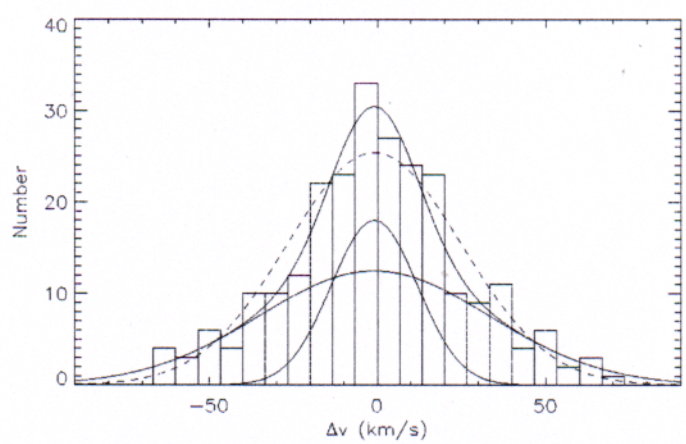
Olszewski et al. (1991); star clusters across the face of LMC



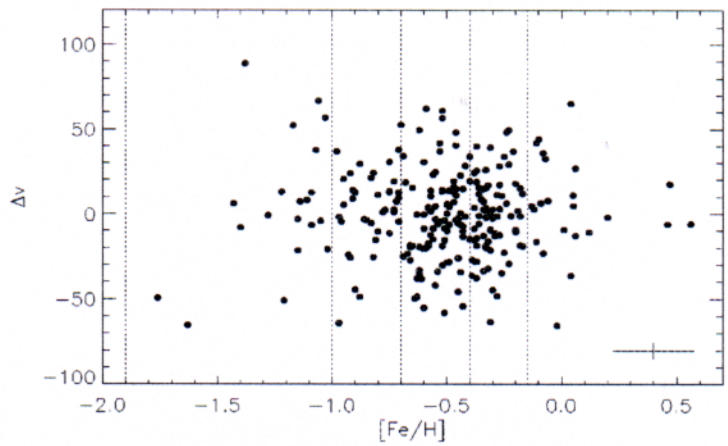
Velocities reveal *at least* 2 distinct components:

35% thin disk ($\sigma_{\Delta v}$ = 12 km/s)

65% thick disk/flattened halo ($\sigma_{\Delta v}$ = 34 km/s)

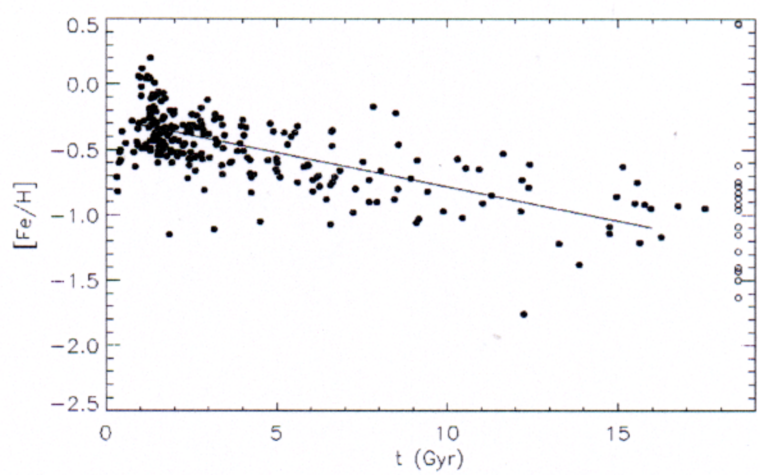


The metallicity ranges of the two LMC components show significant overlap.



Age – Metallicity Relationship in the LMC

(–0.05 dex/Gyr and intrinsic $\sigma_{[Fe/H]} \approx$ 0.16 dex)

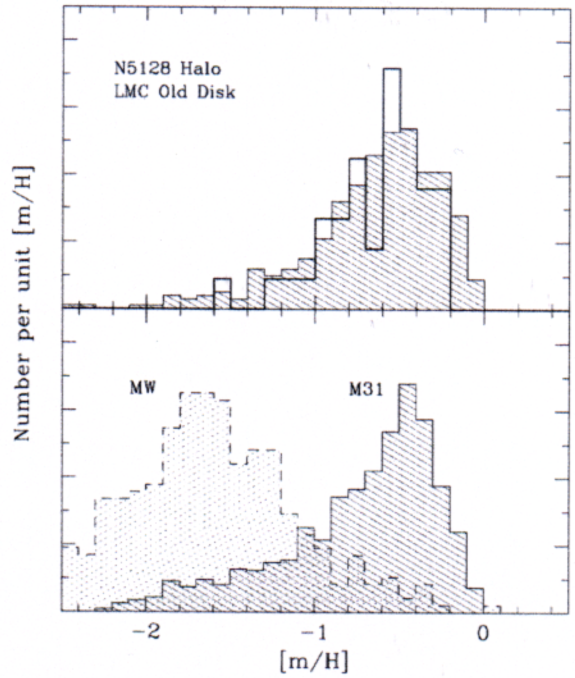


• Halo of NGC 5128 = Centaurus A (Harris & Harris 2000)

• Disk of the LMC (Cole, S-H & Gallagher 2000)

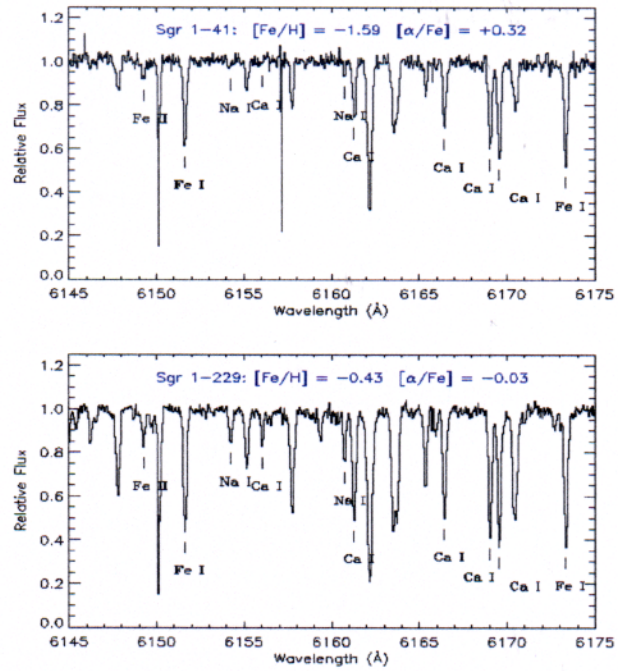
• Halo of M31 = Andromeda (Durrell et al. 2001)

• Halo of the Milky Way (Ryan & Norris 1991)



[Fe/H], Element Ratios & Ages of Stars in dSphs

- Keck I + HIRES spectra of dSph stars:
  14 stars in Sagittarius dSph
  8 stars in Sculptor dSph
  10 stars in Ursa Minor dSph
- Spectra have 40 ≤ S/N ≤ 80 and R = 43,000
- Abundances for 20 different chemical elements:
  O, Na, Mg, Al, Si, Ca, Ti, Mn, Fe, Ni, Y, Ba, La, Eu...
- Ages derived from [Fe/H], [α/Fe], Mbol, Teff and Padova Isochrones (Girardi et al. 2000)
- Sagittarius dSph (T. Smecker-Hane & A. McWilliam 2003)

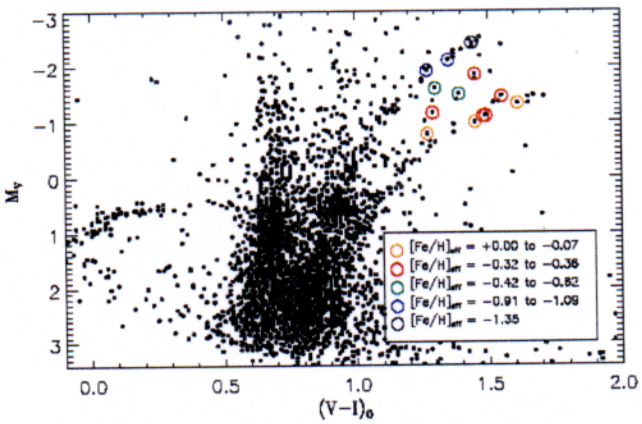


Chemical Abundances and Ages in the Sgr dSph

- EWs measured with GETJOB (McWilliam 1995)
- Stellar parameters (Mbol, Teff, log g) derived from a combination of photometric and spectroscopic techniques taking into account stellar age
- Abundances derived using spectral sythesis (MOOG; Sneden 1973) and 64-layer Kurucz (1994) model atmospheres
- Ages derived from interpolating Padova Isochrones (Girardi et al. 2000) in the (Mbol, Teff) plane for the derived "effective [Fe/H]" as discussed by Salaris et al. (1993):

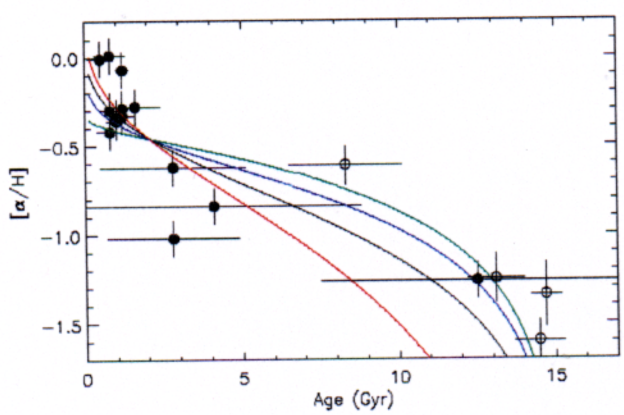
$$[Fe/H]_{eff} = [Fe/H] + \log(0.638 \times 10^{[\alpha/Fe]} + 0.362)$$

Effective Metallicity and Position in the CMD



$$[\mathrm{Fe/H}]_{\mathrm{eff}} = [\mathrm{Fe/H}] + \log(0.638 \times 10^{[\alpha/\mathrm{Fe}]} + 0.362)$$

Age – Metallicity Relationship

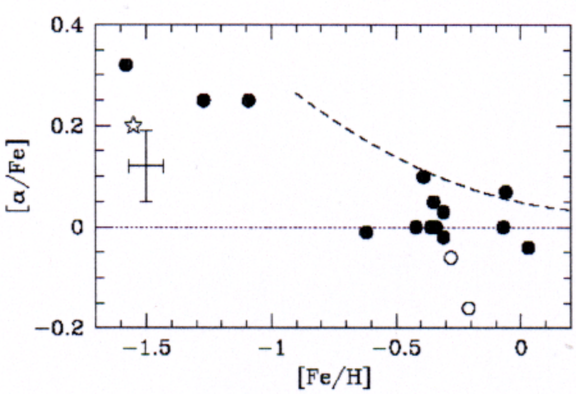


- Filled circles = Sgr dSph stars
- Open circles = 4 Sgr globular clusters
- α = [Ca + Si + Ti]/3
- Note that the instantaneous recycling approx is probably more applicable to α than Fe.

Theoretical Yields from Stellar Nucleosynthesis

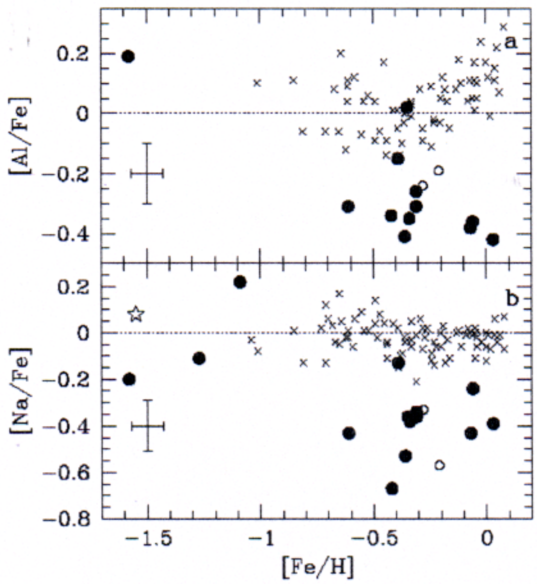
- Type II supernovae = core collapse of a massive, M ⑨ 7 $M_{\odot}$, star
  [α/Fe] = +0.35 (McWilliam 1997; see also theoretical yields cf. Woosley,Timmes & Weaver 1993)
  Ejected ≤ 10^7 yr after stars form
- Type Ia supernovae = accretion induced collapse of a white dwarf
  [α/Fe] = −0.36 (W7 model; Thielemann, Nomoto & Yokoi 1986)
  Ejected from ~ 0.1 Gyr to *many* Gyr after stars form
- [α/Fe] = 0 implies that 70% of the Fe is manufactured in SNe Ia

[α/Fe] verses Metallicity



- [α/Fe] for metal-poor Sgr stars and M54 are similar to Galactic halo stars, reflecting typical Type II yeild, [α/Fe] =+0.35.
- [α/Fe] for metal-rich Sgr stars is about 0.1 dex lower than solar nhbd relationship, reflecting a larger ratio of Type Ia : Type II ejecta in Sgr (70%).

[Al/Fe] and [Na/Fe] verses Metallicity



- [Al/Fe] and [Na/Fe] ratios for the metal-poor Sgr stars are similar to solar nbhd stars.
- [Al/Fe] and [Na/Fe] ratios for metal-rich Sgr stars are 0.35 and 0.4 dex lower than solar nbhd stars!
- Very little or no Na and Al are produced in Type Ia Sne, but some α elements are.
- Again, this suggests ≈70% Fe from SNe Ia.

Neutron Capture Elements created in the r=rapid and s=slow processes

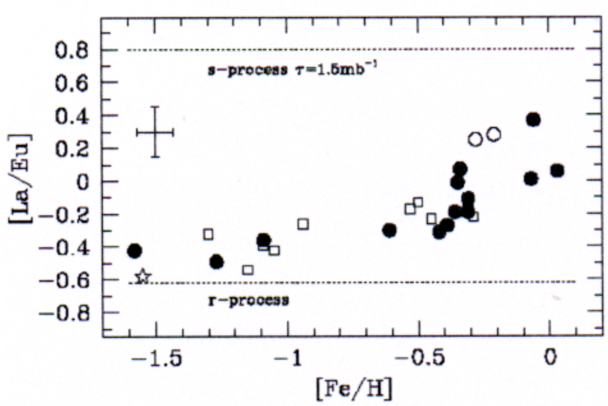
r-process Elements

- Nucleosynthesis Site
  - *Probably* low mass Type II SNe, stars with initial masses of $7\ M_{\odot} < M < 8\ M_{\odot}$
- Example = Eu
  - 95% of the Eu in the Sun is made in the r-process (Burris et al. 2000)

s-process Elements

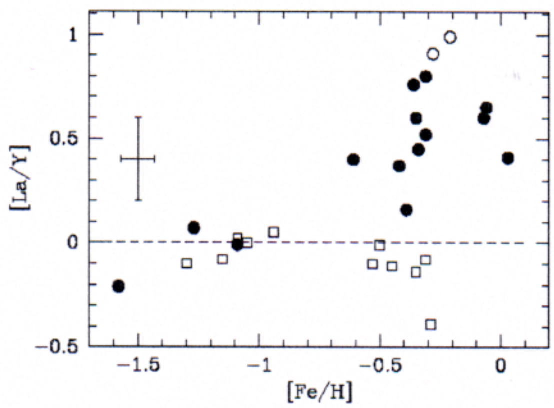
- Nucleosynthesis Site:
  - Thermally pulsing AGB stars with low mass, $1.2\ M_\odot \le M \le 3\ M_\odot$, whose main sequence lifetimes are $\approx$ 3 Gyr to 0.3 Gyr, respectively
- Low Mass Peak:
  Sr, Y, Zr, Nb, Mo
  - 85% of Y in the Sun comes from the s-process
- High Mass Peak:
  Ba, La, Ce, Pr, Nd, Sm
  - 88% of Ba in the Sun comes from the s-process
  - 75% of La in the Sun comes from the s-process
- The ratio of [hs/ls], e.g., [La/Y], is predicted to be a strong function of the initial metallicity of the stars (c.f., Busso, Gallino, Wasserburg 1999), as seen observationally in Galactic stars.

Ratio of [s/r] elements verses Metallicity



- Metal-rich Sgr stars show an every increasing ratio of s to r-process material as a function of metallicity.

Ratio of [hs/ls] verses Metallicity



- The high ratio of [hs/ls] is indicative of enrichment from metal-poor AGB stars with [Fe/H] <~ −1.5
- Thus the metal-poor stars provided the s-process enrichment! This material stayed bound to Sgr and was recycled into later stellar generations.

Conclusions from Sgr dSph Results

- Sgr has a very complex stellar population: [Fe/H] ≈ 0 to -1.5, and ages of ≈ 0.5 to 14 Gyr.
- A significant amount of mass loss is implied. Is the recent high metallicity due to SF going to completion or was Sgr a *much* more massive galaxy (> LMC)?
- The metal-poor, [Fe/H] < -1, stars are consistent with being enriched only by Type II SNe, similar to Galactic halo stars.
- However, the metal-rich stars are enriched by significant amounts of Type Ia and Type II SNe, and by s-process material created in low mass, low metallicity, AGB stars, with [Fe/H] ≈ – 1.5 ejected on timescales of ≈ 0.3 Gyr to 3 Gyr.

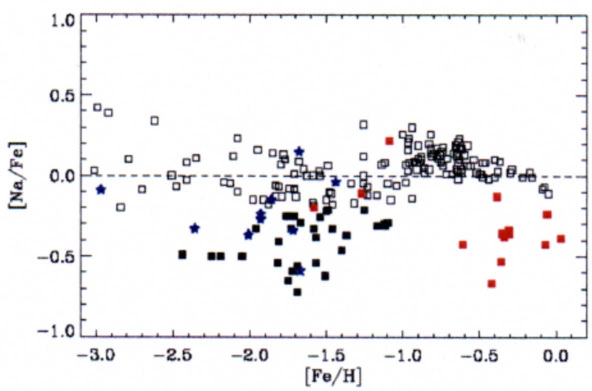
General Conclusions

- The nearby dwarf galaxies – even the most simplest ones, the lowest mass dSphs – have had surprisingly complex star formation histories and chemical evolution.
- Studying nearby dwarfs in detail with a combined program of CMDs and low- and high- dispersion spectroscopy gives powerful constraints on the physical processes that regulate galaxy evolution and valuable constraints on the hierarchical formation of more massive galaxies.

Implications for Merging History of the Milky Way

- Observations of element ratios as a function of metallicity in dSphs, the LMC, and Galactic stellar populations (bulge, halo, thick and thin disk) can be compared to infer clues about the heirarchical formation of the Milky Way.
- However one must remember that many of the dSphs have formed stars over many Gyr, ceasing active star formation only in the last 2 to 3 Gyr, while the stars in the Milky Way thick disk and halo are predominately old (ages > 8 Gyr). Therefore we need to probe the range of metallicities in the dSphs to adequately quantify the older, more-metal poor, component in them in order to form a fair comparison. More data is needed, but at least we can begin this comparison keeping this fact in mind.

[Na/Fe] verses Metallicity

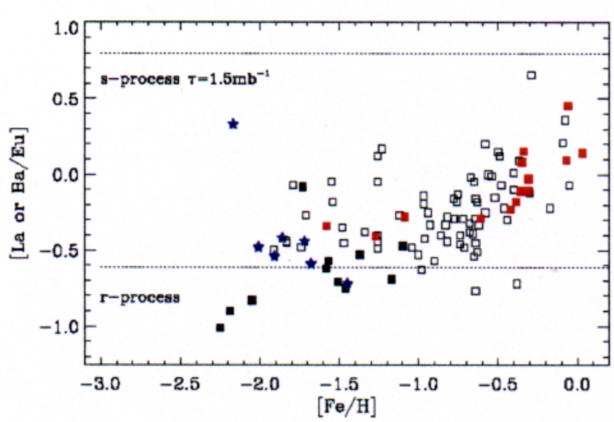


Galactic Stars (Fulbright 2000):
- □ [Na/Fe] ≥ − 0.2
- ■ [Na/Fe] < −0.2

Sgr dSph (Smecker-Hane & McWilliam 2003)

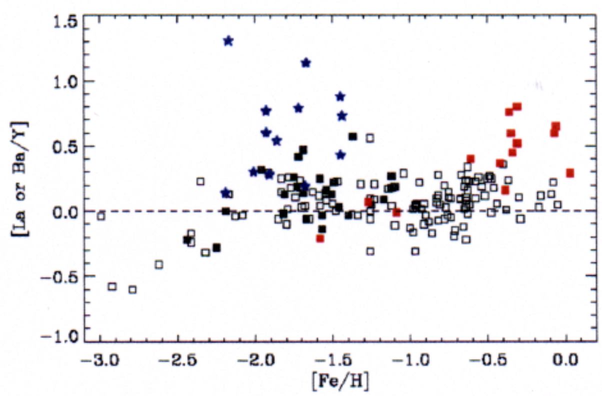
Other dSph stars (Shetrone, Côté & Sargent 2001)

Ratio of [s/r] elements verses Metallicity



- Little evidence for large amounts of s-process elements in Shetrone et al. (2001) dSph stars, but selection effects important, and new data (Shetrone, et al. 2003) for dSphs with more complex SFHs do show metal-rich end enriched in s-process.

Ratio of [hs/ls] elements verses Metallicity



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