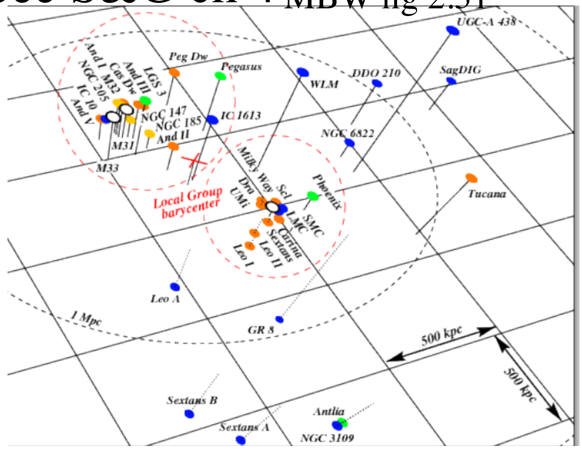
Local Group See S&G ch 4 MBW fig 2.31

- Our galactic neighborhood consists of one more 'giant' spiral (M31, Andromeda), a smaller spiral M33 and lots of (>35 galaxies), most of which are dwarf ellipticals and irregulars with low mass; **most are satellites of MW, M31 or M33.** The gravitational interaction between these systems is complex but the local group is apparently bound.
- Major advantages
  - close and bright- all nearby enough that individual stars can be well measured as well as HI, H_2, IR, x-ray sources and even γ-rays
  - wider sample of universe than MW (e.g. range of metallicities, star formation rate etc etc) to be studied in detail



–allows study of dark matter on larger scales and first glimpse at galaxy formation

–calibration of Cepheid distance scale

Next Presentation

- The Milky Way's bright satellites as an apparent failure of ΛCDM

2012MNRAS.422.1203B

Ken Koester **Nov 6**

The presentation on Nov 13 is on

The Origin Of The Mass–metallicity Relation:

Insights From 53,000 Star-forming Galaxies In The SDSS

Christy A. Tremonti focus on sec 1,3,6 and 8 Laura L.

We will now slow down a bit, the semester is 2/3 over and I want the class to start focusing on the term project . After Laura only 4 more presentations Jialu Nov15, Weizhe Nov 20 , Liz Nov 27 and Tom Nov 29

Last day of class is Dec 11 and the project is due Dec 4- Please send me your project titles by Nov 10

Local group References

- The Observed Properties of Dwarf Galaxies in and around the Local Group McConnachie, Alan W. 2012AJ....144....4
- ARA&A1999, V 9, pp 273-318 The local group of galaxies S. van den Bergh
- Star formation histories in local group dwarf galaxies Skillman, Evan D. New Astronomy Reviews, v. 49, iss. 7-9 p. 453-460.
- Tolstoy, Eline; Hill, Vanessa; Tosi, Monica

Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group 2009ARA&A..47..371T

Image of Local Group to Scale S&G Fig 4.1

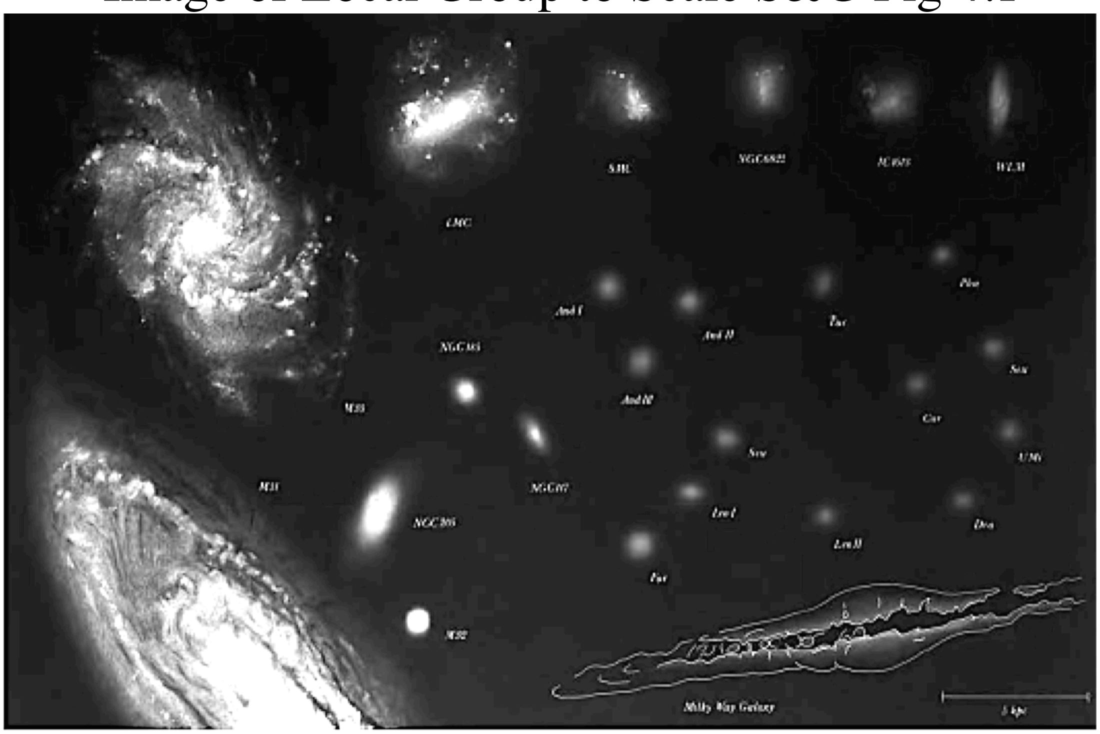
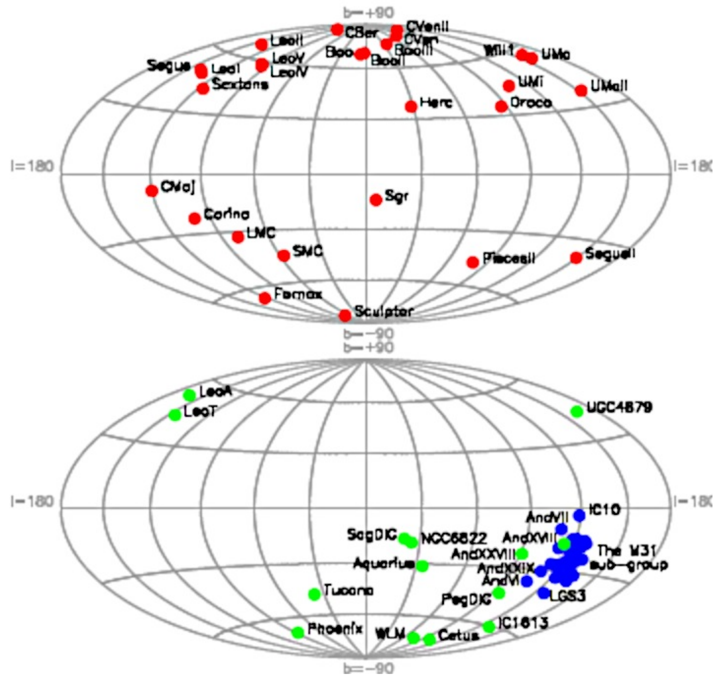


Fig. 4.1. Galaxies of the Local Group, shown to the same linear scale, and to the same level of surface brightness. The spiral and irregular galaxies stand out clearly, while the dwarf spheroidals are barely visible – B. Binggeli.

Where are the Local Group Galaxies

- Red are satellites of the MW
- Blue are satellites of M31
- Green are 'unassociated' galaxies (McConnachie 2012)



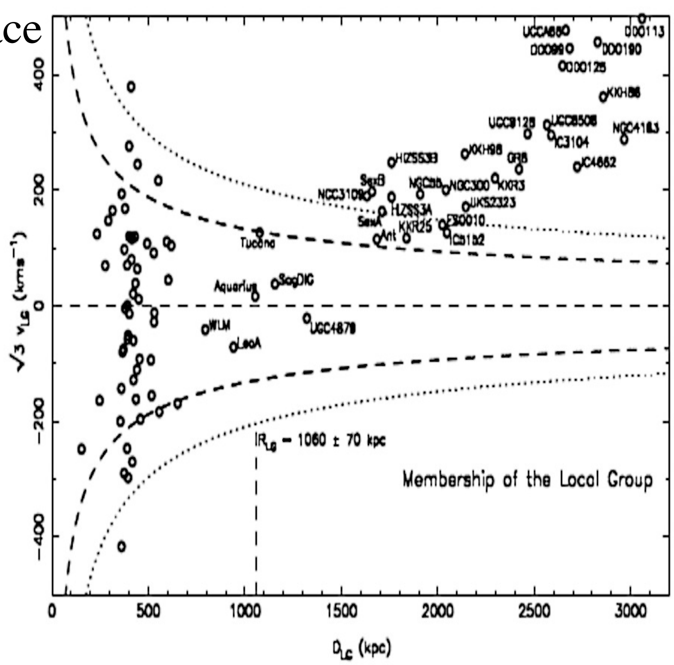
Galactic coordinates

Where are the Local Group Galaxies In Velocity Space

- Dashed curves indicate the escape velocity from a point mass of ~2x $10^{12} M_{\odot}$.
- Dotted curves indicate the escape velocity from a point mass of $5x10^{12} M_{\odot}$, the approximate total dynamical mass of the Local Group as implied from the timing argument (e.g., Lynden-Bell 1981 a classic paper

The Observatory, vol. 101, p. 111-114)

Local group-centric velocity

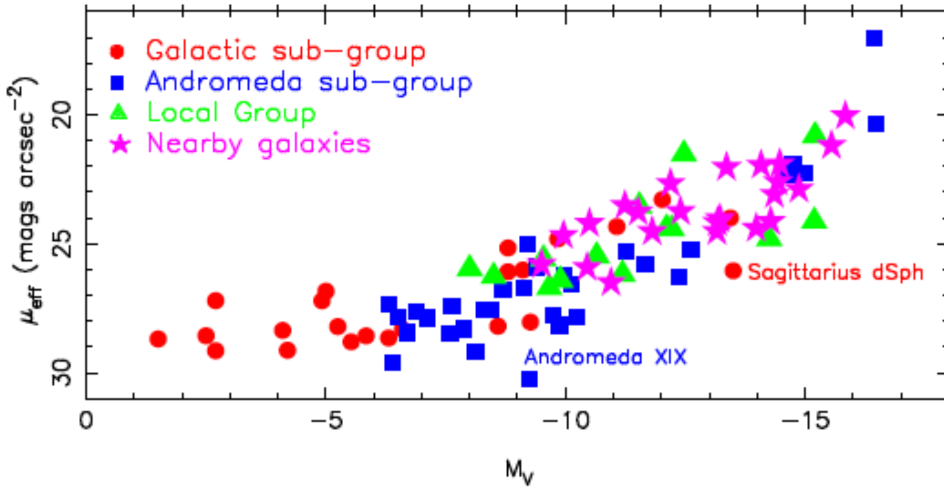


distance from the barycenter of the Local Group

(McConnachie 2012)

Selection Effects in Finding Low Luminosity Galaxies in Local Group

- From the ground very hard to go below 30 mag/sqarcsec surface brightness in optical bands
- At low surface brightness find galaxies by looking at clumps of red giant stars (McConnachie 2012)

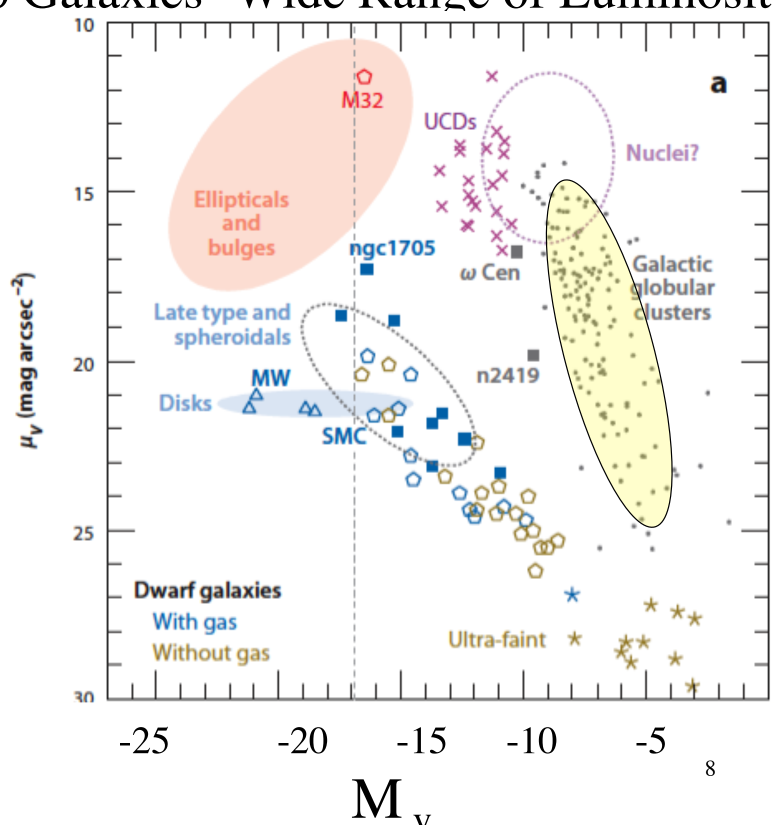


Local Group Galaxies -Wide Range of Luminosity

- Local Group dwarfs galaxies trace out a narrow line in the surface brightness luminosity- plane

(Tolstoy et al 2009)

see table 4.1 in S&G



Comparison of Galaxies and Globulars

- Comparison of dwarf galaxies in the local group and globular clusters
- Notice that the 'new' DES candidates are dimmer and smaller

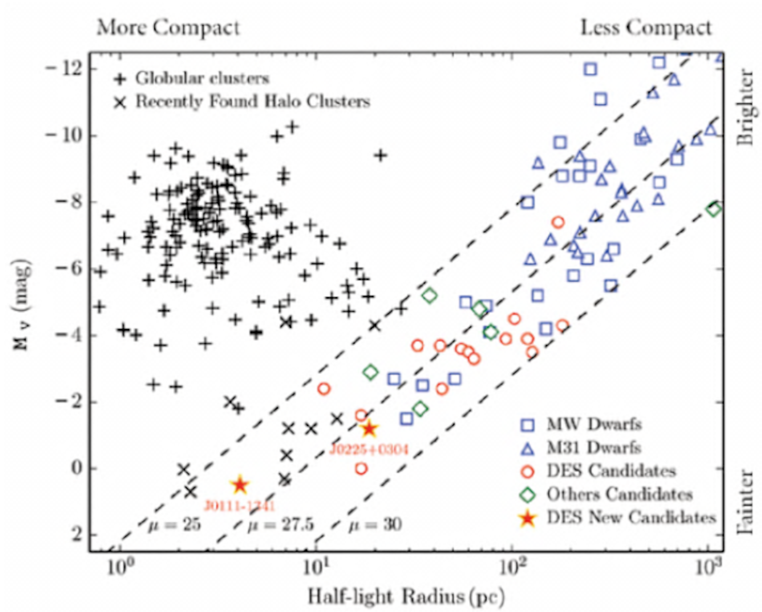
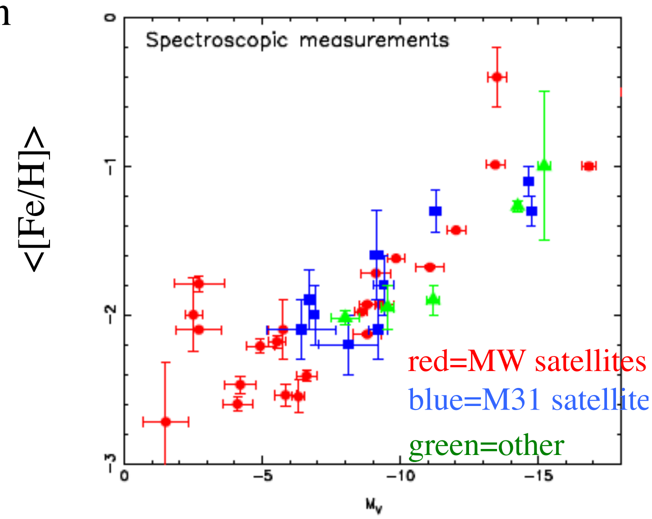


Figure 2. Absolute magnitude versus half-light radius for globular clusters and dwarf

Wide Range of Luminosities and Chemical Composition

- MW/M31~$2 \times 10^{10} L_{v\odot}$
- LMC~$2 \times 10^{9} L_{v\odot}$
- Formax dSph $1 \times 10^{7} L_{v\odot}$
- Carina dSph $3 \times 10^{5} L_{v\odot}$

- Because of closeness and relative brightness of stars the Color Magnitude Diagram combined with spectroscopy of resolved stars produces 'accurate'
  - star formation histories
  - Chemical evolution



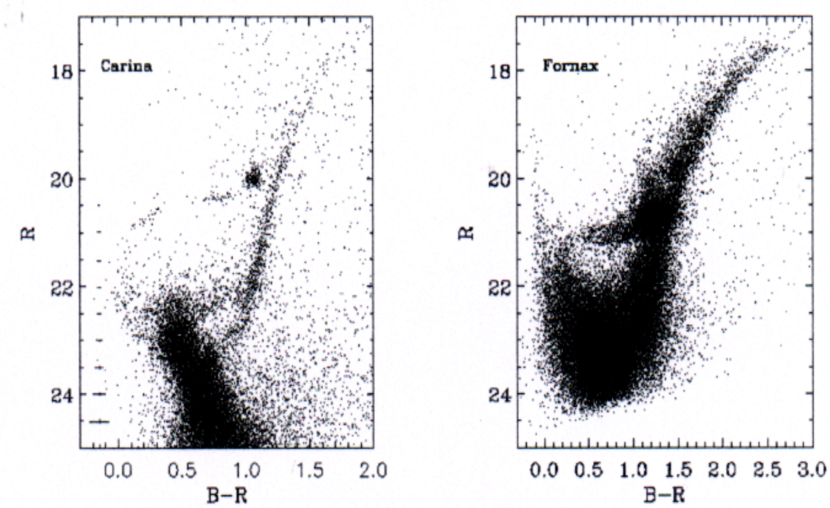
M_v(mag)

T. Smecker-Hane

Despite wide variety of 'local' environments (near/far from MW/M31) trends in chemical composition seem to depend primarily on galaxies luminosity/mass

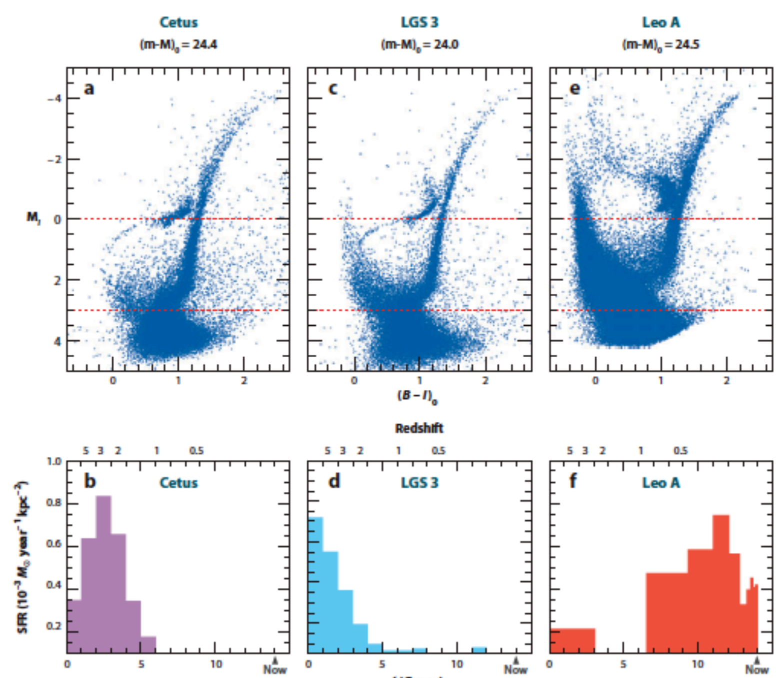
Star Formation Histories

- Analysis of CMDs shows presence of both old and (some) young stars in the dwarfs -complex SF history
- The galaxies do not show the same SF history- despite their physical proximity and being in a bound system
- Their relative chemical abundances show some differences with low metallicity stars in the MW.



Star Formation Histories Local Group Dwarfs

- With HST can observed color magnitude diagram for individual stars in local group galaxies in MS
- Using the techniques discussed earlier can invert this to get the star formation history
- Note 2 extremes: very old systems Cetus, wide range of SF histories (Leo A)
- (Tolstoy, Hill, Tosi Annual Reviews 2009)

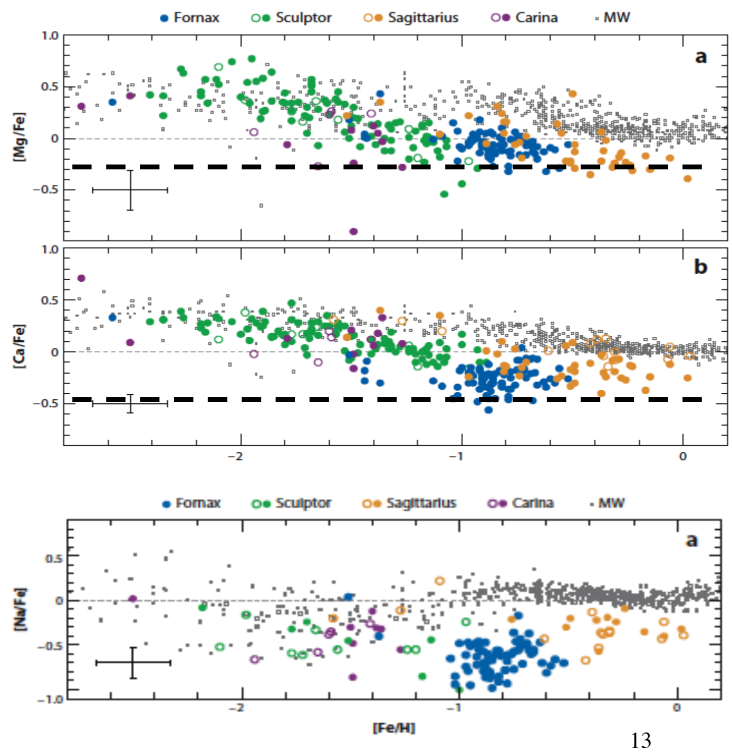


0 10 now

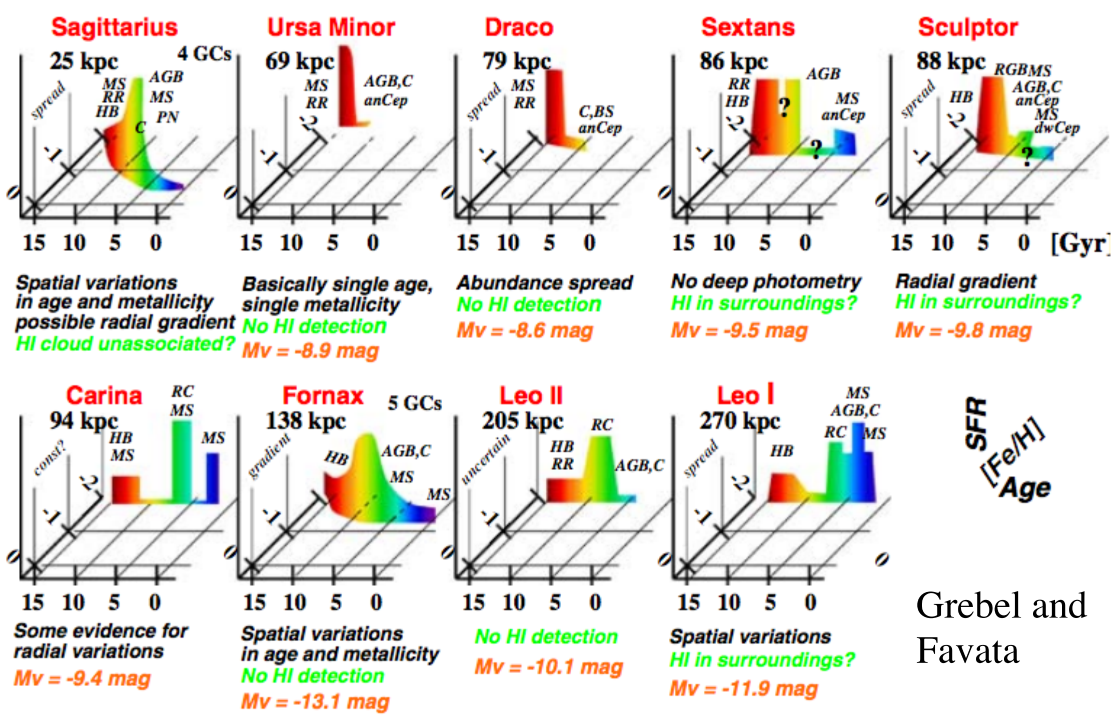
t (Gyr)

- Overall metallicity of LG dwarfs is low but some patterns similar, others different to stars in MW (black dots- Tolstoy et al 2009)-
- How to reconcile their low observed metallicity with the fairly high SFR of the most metal-poor systems many of which are actively star-forming
- best answer metal-rich gas outflows, e.g. **galactic winds**, triggered by supernova explosions in systems with shallow potential wells, efficiently remove the metal-enriched gas from the system.
- In LG wind models can be well constrained by chemical abundance observations.

Metallicities In LG Dwarfs Vs MW

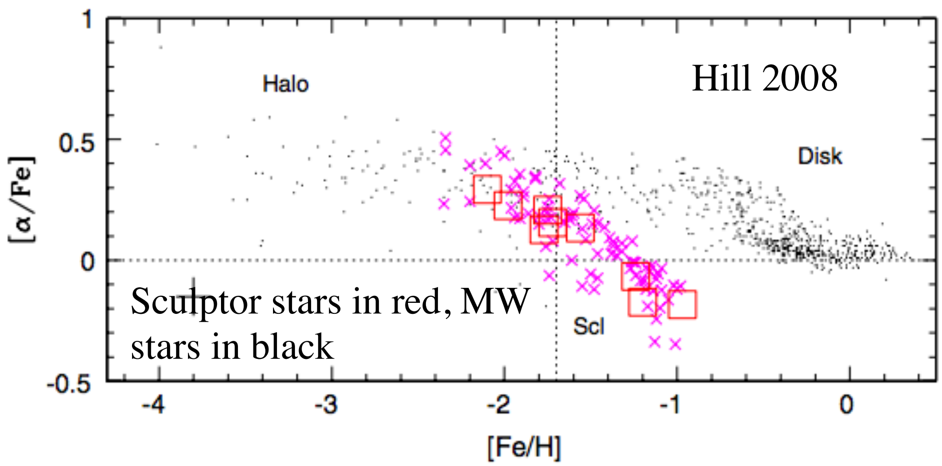


History of SFR In Local Group Dwarfs



Grebel and Favata

Abundances in Local Group Dwarfs



- Clear difference in metal generation history

Closed BOX MBW 10.4.2

- Consider a system consisting of gas and stars
- the masses in gas and stars by $M_{gas}(t)$ and M_{star}(t)
- no mass flow into or out of the system, so that the total mass $M_{tot} = M_{gas}(t)+M_{star}(t)$ is constant
- To form stars consume gas so
- $dM_{gas}(t)/dt= -\Psi(t)+\mathcal{E}(t)$,where Ψ(t) is the star formation rate and

$\mathcal{E}(t)$ is the rate at which stars return mass to the system (e.g. SN, planetary nebulae etc)

The time evolution of metals is then $d(ZM_{gas}(t)_s)/dt = -Z\Psi(t)+\mathcal{E}(t)_{Z'}$ where Z is the metallicity of the gas defined by $Z=M_z/M_{gas}$

If we assume instantaneous re-cycling such that all stars more massive than m_{lim} have very short lifetimes while those with lower mass have very long lifetimes then the return rate can be written as an integral over the IMF times the fraction of the mass ejected

Closed BOX MBW 10.4.2

- One can solve this to get
- $Z(t) = Z(0)+y_Z\ln[M_{gas}(0)/M_{gas}(t)]$

(10.123)

- where $M_{gas}(0)$ and $Z(0)$ are, respectively, the gas mass and metallicity at t=0
- If the system starts as ALL gas then we can write this as
- $Z(t) = Z(0)\text{-}y_Z\ln[M_{gas}(t)/M_{total}]$
- metallicity of gas grows with time logarithimcally
- where metal yield, y_Z, is defined as the ratio between the mass of *newly produced* metals (i.e. those metals produced in the star via nucleosynthesis) and the total mass which remains locked up in the remnants

thus the metallicity is determined by the metal yield and the gas mass fraction as a given time

We can use this solution to predict the metallicity distribution of stars when
$M_{star}(<Z)=M_{tot}-M_{gas}(t)=M_{tot}\{1-\exp([Z-Z(0)]/y_z)\}$ **10.126**

Please read 10.4.3 for inflow and outflow solutions

Closed Box Approximation-Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388 S&G 4.3.2

- To get a feel for how chemical evolution and SF are related (S+G q 4.13-4.17)- but a different approach (Veilleux 2010)

- at time t, mass ΔM_{total} of stars formed, after the massive stars die left with

$\Delta M_{low\ mass}$ which live 'forever',

- massive stars inject into ISM a mass $p\Delta M_{total}$ of heavy elements (p depends on the IMF and the yield of SN- normalized to total mass of stars).
- Assumptions: galaxies gas is well mixed, no infall or outflow, high mass stars return metals to ISM faster than time to form new stars)

$M_{total}=M_{gas}+M_{star}$=constant ($M_{baryons}$) ; $M_h$mass of heavy elements in gas $=ZM_{gas}$

dM'_{stars} =total mass made into stars, dM''_{stars} =amount of mass instantaneously returned to ISM enriched with metals

$dM_{stars} = dM'_{stars} - dM''_{stars}$ net matter turned into stars

define y as the yield of heavy elements- yM_h=mass of heavy elements returned to ISM

Z is the metallicity

Closed Box- continued

- Net change in metal content of gas
- $dM_h = y\, dM_{star} - Z\, dM_{star} = (y - Z)\, dM_{star}$

- Change in Z since $dM_g = -dM_{star}$ and $Z = M_h/M_g$ then
- $dZ = dM_h/M_g - M_h\, dM_g/M^2_g = (y - Z)\, dM_{star}/M_g + (M_h/M_g)(dM_{star}/M_g) = y dM_{star}/M_g$
- $dZ/dt = -y(dM_g/dt)\, M_g$

- If we assume that the yield y is independent of time and metallicity (Z) then
- $Z(t) = Z(0) - y \ln M_g(t)/M_g(0) = Z(0) = y \ln \mu$ metallicity of gas grows with time as log

mass of stars that have a metallicity less than Z(t) is $M_{star}[< Z(t)] = M_{star}(t) = M_g(0) - M_g(t)$ or

$M_{star}[< Z(t)] = M_g(0) * [1 - \exp((Z(t) - Z(0))/y]$

when all the gas is gone mass of stars with metallicity Z, Z+d Z is

$M_{star}[Z]\ \alpha\ \exp((Z(t) - Z(0))/y)\, d Z$ is we use this to derive the yield from data

$Z(today) \sim Z(0 - y\ln[M_g(today)/M_g(0)]$; $Z(today) \sim 0.7\, Z_{sun}$

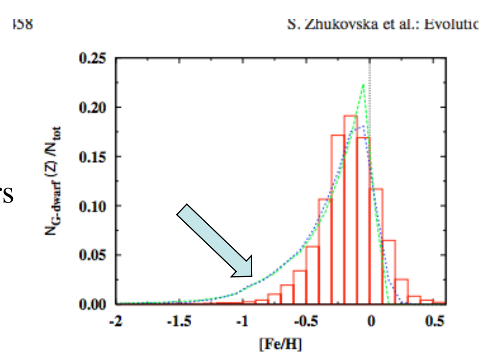
since initial mass of gas was sum of gas today and stars today $M_g(0) = M_g(today) + M_s(today)$ with $M_{stars} today) \sim 40 M_\odot/pc^2$ $M_g(today) \sim 10 M_\odot/pc^2$

get $y = 0.43\, Z_{sun}$ go to pg 180 in text to see sensitivity to average metallicity of stars

Closed Box- Problems

- Problem is that closed box connects todays gas and stars yet have systems like globulars with no gas and more or less uniform abundance.
- Also need to tweak yields and/or assumptions to get good fits to different systems like local group dwarfs.
- Also 'G dwarf' problem in MW (S+G pg 180-181) and different relative abundances (e.g C,N,O,Fe) amongst stars s

Green is closed box model
red is observations of local stars
see eq 4.1.6 S&G



- Go to more complex models - leaky box (e.g inflow/outflow);
  - if we assume outflow of metal enriched material g(t); and assume this is proportional to star formation rate $g(t) = c dM_s/dt$;
  - result is $Z(t) = Z(0) - [(y/(1+c)) * \ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change abundance distribution (shifts mean)

Leaky-Box Model

Veilleux

- *If there is an outflow of processed material, g(t), the conservation of mas becomes*

$$dM_g/dt + dM_s/dt + g(t) = 0$$

see MBW 10.4.3

- *And the rate of change in the metal content of the gas mass becomes*

$$dM_h/dt = y\, dM_s/dt - Z\, dM_s/dt - Zg$$

- *Example:* Assume that the rate at which the gas flows out of the box is proportional to the star formation rate:
  - $g(t) = c\, dM_s/dt$ (c is a constant; c = 0.01 - 5)
  - As before $dZ/dt = y * (dM_s/dt) / M_g(t)$
  - Where $dM_s/dt = -[1/(1+c)]\, dM_g/dt$
  - So $dZ/dt = -[y/(1+c)] * [1/M_g] * dM_g/dt$
  - Integrating this equation, we get $\boxed{Z(t) = Z(0) - [y/(1+c)] * \ln[M_g(t)/M_g(0}$
  - The only effect of an outflow is to reduce the yield to an effective yield = y/(1

Accreting-Box Model

- *Example:* Accretion of pristine (metal-free) gas to the box
- Since the gas accreted is pristine, the mass of heavy elements produced in a SF episode is

$$dM_h/dt = (y - Z)\, dM_s/dt$$

- However, for the conservation of mass in the box becomes:

$$dM_g/dt = -dM_s/dt + f(t)$$

- Consider the simple case in which the mass in gas in the box is constant. This implies then

$$dZ/dt = 1/M_g * [(y - Z)\, dM_s/dt - Z\, dM_g/dt] = 1/M_g * [(y - Z)\, dM_s/dt]$$

Accreting-Box Model

- *Integrating and assuming that $Z(0) = 0$*

  $$Z = y\,[1 - e^{-M_s/M_g}]$$

- *Therefore when $M_s >> M_g$, the metallicity $Z \sim y$*
- *The mass in stars that are more metal-poor than Z is*

  $$M_s(< Z) = - M_g \ln(1 - Z/y)$$

- *In this case, for $M_g \sim 10\ M_{sun} / pc^2$ and $M_s \sim 40\ M_{sun}/pc^2$, and for $Z = 0.7\ Z_{sun}$, then $y \sim 0.71\ Z_{sun}$. Thus the fraction of stars more metal-poor than $0.25\ Z_{sun}$ is $M(<0.25)\,/M(<0.7) \sim 10\%$, in much better agreement with the observations of the solar neighborhood*

Leaky box

Outflow and/or accretion is needed to explain

- Metallicity distribution of stars in Milky Way disk
- Mass-metallicity relation of local star-forming galaxies
- Metallicity-radius relation in disk galaxies
- Metallicity near the sun (g dwarf problemEquation 4.16 requires
- $M(<Z/4)/M(<Z) \approx 0.4$; e.g nearly half of all stars in the local disk should have less than a quarter of the Sun’s metal content but of a sample of 132 G dwarf stars in the solar neighborhood, just 33 were found to have less than 25% of the solar abundance of iron, and only one below 25% of the solar fraction of oxygen

- But simple closed-box model works well for bulge of Milky Way
- Outflow and/or accretion is needed to explain

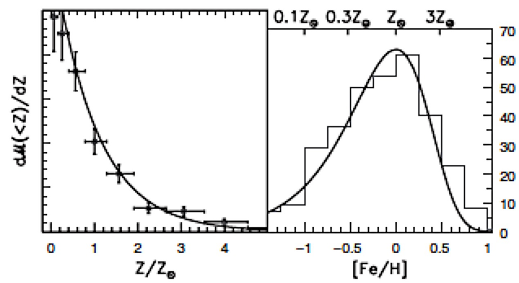
Metallicity distribution of stars in Milky Way disk

Mass-metallicity relation of local star-forming galaxies

Metallicity-radius relation in disk galaxies

Merger-induced starburst galaxies

Mass-metallicity relation in distant star-forming galaxies



Galactic **bulge** metallicity distributions of stars S&G fig 4.16- solid line is closed box model