Chemical Evolution of the Milky Way and Local Group Galaxies

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In the beginning there was… Hydrogen, Helium and a little bit of Lithium plus a lot of other strange things… like dark matter… the Universe was very smooth & uniform

... we see today a complex and dynamic universe full of galaxies and stars – how did this happen?
Simulating the Formation of Galaxies

100 Mpc/h

stars in yellow

COLD DARK MATTER

now

Time (fraction of age of Universe)

7% z ~ 6

30% z ~ 1

MODEL!!!

http://www.mpa-garching.mpg.de/~volker/ (SpringelV homepage)
The Nearest Galaxy...  

...congeries stellularum...  

Galileo Galilei (1609)
Outer regions: dominated by gas rich quiescently evolving dwarf irregulars

Near centres of mass: gas-less pressure supported dSphs

Anomalies: more distant dSph

The Local Group

M31, MW
$\sim 10^{11-12} \, M_\odot$

M33 $\sim 5 \times 10^{10} \, M_\odot$

Mateo 2008, Garching workshop
Milky Way - Halo

- Dwarf stars: $\sim 10^{8-9} M_\odot$
- Ultra-faints: $\leq 10^{4-5} M_\odot$
- LMC: $\sim 10^{10} M_\odot$

Mateo 2008, Garching workshop
The Field of Streams

The Field of Streams

Globular Clusters
(and a few ultra-faints)

~140 globular clusters, 65% <8kpc from centre

Mateo 2008, Garching workshop
Global Properties of Galaxies

based on Kormendy 1985; Binggeli 1994
see also Belokurov et al. 2007
Resolved Stars

now

Big Bang

Low mass stars < 1M☉

direct observations of galaxies

Tolstoy E.

Spectroscopy

Metallicity

“pristine” atmosphere

Imaging

Age

nuclear burning

Resolved Stars

Tolstoy E.

Age of Universe (Billions of Years)

Redshift

0 2 4 6 8 10 12 14 16 18 20

10 5 3 2 1 0.6 0.4 0.3 0.2

now
Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

Big Bang

- The Big Bang
  - The Universe filled with ionized gas
  - The Universe becomes neutral and opaque
  - The Dark Ages start

~ 300 thousand years

- Galaxies and Quasars begin to form
  - The Reionization starts

~ 500 million years

- The Cosmic Renaissance
  - The Dark Ages end
  - Reionization complete, the Universe becomes transparent again

~ 1 billion years

- Galaxies evolve

~ 9 billion years

- The Solar System forms

~ 13 billion years

- Today: Astronomers figure it all out!
Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

The Big Bang
The Universe filled with ionized gas
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S.G. Djorgovski et al. & Digital Media Center, Caltech
Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

Big Bang

A Schematic Outline of the Cosmic History

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Time since the Big Bang (years)

- ~ 300 thousand
- ~ 500 million
- ~ 1 billion
- ~ 9 billion
- ~ 13 billion

Galaxies: Snapshots in Time

- 2 Billion Years
- 5 Billion Years
- 9 Billion Years

Age of the Universe

Today: 14 Billion Years

S.G. Djorgovski et al. & Digital Media Center, Caltech
Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

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S.G. Djorgovski et al. & Digital Media Center, Caltech

present

z = 30
Neutral Hydrogen

first objects form

z = 15
Stars Form in More Massive Halos

Ionized Hydrogen

HII regions overlap

z = 10

present
**Cosmic History**

http://wmap.gsfc.nasa.gov/ (NASA home page)

A Schematic Outline of the Cosmic History

- **The Big Bang**
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Galactic Archaeology…

We want to study how the properties of the universe change – but it is difficult to do it directly – so we can try indirectly:

Stars form from gas through time – they live a long time – and if we can measure their properties at different ages we learn about galaxy formation & evolution.
Part I
Resolved Imaging

- Star Formation Histories -
Colour-Magnitude Diagram (CMD)

SFHs in the Local Group

Figure 43. Star formation histories of elliptical and spheroidal galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.

Figure 44. Star formation histories of irregular and transition-type galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.
We can't study all galaxies with the same detail and beyond the Local Group it becomes particularly difficult with current facilities.
Fractional age distributions

Assuming constant SFR over 13Gyr

Cignoni & Tosi 2010, Advances in Astronomy, pp. 1-26
Cepheid Variable Stars

Period-Luminosity relation

\[ (m-M_V)_0 = 5 \log_{10} d(\text{pc}) - 5 (+A) \]

Accurate DISTANCES

Harlow S., 1961, Harvard University Press

\[ M_V = -2.80 \log_{10} P - 1.43 \]
Birth of Extragalactic Astronomy

Extragalactic nebulae

Hubble used Cepheid variable stars to show that distances to M31, M33 and NGC6822 are without doubt BEYOND our own Galaxy.
RR Lyr Variable Stars

**Oosterhoff Dicotomy**

Oosterhoff (1939)

Galactic Globular clusters plus X-gal globulars + dwarfs

**Period**

$\langle P_{ab} \rangle$ (d)

**Metallicity**

[Fe/H]

Catelan 2009
RR Lyr Variable Stars

Dichotomy also present in field stars….

Catelan 2004
Carina Dwarf Spheroidal Galaxy

Tolstoy F., Hill V., Tosi M., ARA&A, 46, 371

Mario Mateo
Some hints about evolved populations

$\langle [Fe/H] \rangle \sim -1.1$

$\langle [Fe/H] \rangle \sim -1.2$

$\langle [Fe/H] \rangle \sim -1.4$

See also Tolstoy F., 2010 arXiv 1012.2229
Global Properties

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
M32 – an elliptical in the Local Group

Intermediate age, metal rich system
+ ancient metal poor component

M32 – NGC221 (~760kpc)

M32 – NGC221 (~760kpc)


Global Properties

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
NGC1705: a Blue Compact Dwarf

Annibali et al. (2003)

HST/ACS image

NGC1705 (~5Mpc)
Summary of BCD SFHs

from Tolstoy, Hill & Tosi 2009
Comparing different types in one “region”

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
Scl dSph

86 kpc distance

$M_V = -11.2$

de Boer et al. 2011 A&A, in press
Leo A dI

800 kpc distance

$M_v = -11.7$

8 candidate RR Lyraes (Dolphin et al. 2002); Fiorentino et al., in prep.
VII Zw 403: a Blue Compact Dwarf

Image: multi-colour HST/WFPC2, credit D. Hunter

VII Zw 403 – UGC 6456 (~4.5Mpc)

Lynds et al. 1998
Comparing the different types

\begin{align*}
(m-M)_0 &= 19.7 \\
\text{Scl dSph (CTIO/MOSA)}
\end{align*}

\begin{align*}
(m-M)_0 &= 24.5 \\
\text{Leo A (HST/ACS)}
\end{align*}

\begin{align*}
(m-M)_0 &= 27.6 \\
\text{VII Zw403 (HST/WFPC2)}
\end{align*}
Comparing different types in the transition region

Different SFHs - yet global properties still correlate
dSph, dI & BCDs differ only in that dI & BCD have on-going star formation

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
Cosmological Context

Evolution of SFR density

Hippelein et al. 2003
Star Formation Density in Local Group

Hopkins et al. 2001

\[ H_0 = 75, \, \Omega_M = 0.3, \, \Omega_\Lambda = 0.7 \]
Next lecture I tell you about metallicites and spectroscopy
Part II
- Spectroscopy —
metallicities, abundances &
kinematics
The Crab nebula — 1054 CE “guest star” observed & recorded in China

Type II supernova from a massive star oxygen, iron, heavy elements etc.
...and most stars lose their mass more slowly....

The Helix: a planetary nebula from a Sun-like star, producing carbon, nitrogen etc.
Nucleosynthesis

LOW MASS STAR (the Sun)

main sequence (~8 billion years)

red giant (~100 million years)

Planetary nebula (100 thousand years)

Fe, O, Ca, Mg, Ti…

C, N, Ba

GAS
Nucleosynthesis

LOW MASS STAR (the Sun)

main sequence (~8 billion years)

red giant (~100 million years)

HIGH MASS STAR (20 x Sun)

main sequence (~8 million years,

red super-giant (~100 thousand years)

Supernova

Fe, O, Ca, Mg, Ti, ...

Planetary nebula (100 thousand years)

C, N, Ba

Multiple Shell Burning Supergiant

Protostars

GAS
Nucleosynthesis

LOW MASS STAR (the Sun)
- main sequence (~8 billion years)
- red giant (~100 million years)
-行星 nebula (100 thousand years)

HIGH MASS STAR (20 x Sun)
- main sequence (~8 million years)
- red super-giant (~100 thousand years)
- Supernova
- Fe, O, Ca, Mg, Ti, ...

Planetary nebula (100 thousand years)
- C, N, Ba
A spectrum...

- Fraunhofer (1817) absorption lines in the solar spectrum.
- Kirchhoff (1859) every chemical element has its own spectral lines (a DNA fingerprint).
- Payne[-Gaposchkin] (1925) stars are mostly Hydrogen and Helium.
- nucleosynthesis, Burbidge, Burbidge, Fowler & Hoyle (1957)
We are all made of stardust....

All elements in the Universe heavier than He & Li are formed within stars: NUCLEOSYNTHESIS

These are the abundances in the gas out of which our Sun and our Solar System was formed about 4Gyr ago; other stars formed at other times will be different: CHEMICAL TAGGING
We are all made of stardust....

All elements in the Universe heavier than He & Li are formed within stars: NUCLEOSYNTHEIS

These are the abundances in the gas out of which our Sun and our Solar System was formed about 4Gyr ago; other stars formed at other times will be different: CHEMICAL TAGGING
Chemical Tagging

- **Light Elements** – e.g., O Na Mg Al
  tracers of deep mixing abundances patterns
  (globular clusters versus field stars)

- **α- Elements** – e.g., O Mg Si Ca Ti
  dominated by products of Supernovae II

- **Iron-peak Elements** e.g., V Cr Mn Co Ni Cu Zn
  explosive nucleosynthesis (supernovae I)

- **Heavy Elements (Z > 30)**
  mix of r- and s- process elements
  e.g., s-process  e.g., Ba, La (low mass stellar winds)
  r-process  e.g., Eu (supernovae?)

McWilliam 1997 ARAA, 35, 503
Freeman & Bland-Hawthorn 2002 ARAA, 40, 487
Spectral Types: temperature sequence

\[ L (L_\odot) \]

\[ T (K) \]

O B A F G K M

supergiants
main sequence (dwarfs)
red giants
white dwarfs

Metal lines: Strongest when temperature is low enough that lower ionization stages are populated.

The metal lines become progressively stronger as the temperature cools and dominate in the F, G, K stars.

Spectral Types: temperature sequence

Metal lines: Strongest when temperature is low enough that lower ionization stages are populated.

The metal lines become progressively stronger as the temperature cools and dominate in the F, G, K stars.

\[ T \sim 4000K \]
Molecules!

\[ T \sim 6000K \]
Ionised Metal lines

\[ T < 11000K \]
Dominated by neutral H

\[ T \sim 30000K \]
Highly ionised species

Relative Strength of Spectral Lines

- Ionized Helium
- Neutral Helium
- Hydrogen
- Ionized Metals
- Neutral Metals

Spectral Class:
- O
- B
- A
- F
- G
- K
- M

Relative strengths of lines vs. Molecules (TiO)
Dominant Features in the Spectra of Stars
The Milky Way
Properties of Milky Way...
Disentangling the Galaxy

stellar abundances and kinematics are excellent tools for galactic archaeology.

Venn et al. 2004

Eggen, Lynden-Bell & Sandage
Copenhagen-Geneva Survey of stars in Solar Neighbourhood

Motions during last 250 million years

Nordstrom et al. 2004
Properties of different components

Venn et al. 2004
Stellar Abundances in the Milky Way

compilation by Venn et al. 2004
Stellar Abundances in the Milky Way

compilation by Venn et al. 2004
Stellar Abundances in the Milky Way


[α/Fe] vs [Fe/H]

compilation by Venn et al. 2004
Stellar Abundances in the Milky Way

compilation by Venn et al. 2004

“The Knee”
Stellar Abundances in the Milky Way

Figure 1 A schematic diagram of the trend of $\alpha$-element abundance with metallicity. Increased initial mass function and star formation rate affect the trend in the directions indicated. The knee in the diagram is thought to be due to the onset of type Ia supernovae (SN Ia).

compilation by Venn et al. 2004

“The Knee”
Stellar Abundances in the Milky Way


compilation by Venn et al. 2004

"The Knee"
Stellar Abundances
in the Milky Way

The Knee


compilation by Venn et al. 2004
Stellar Abundances in the Milky Way

“The Knee”

compilation by Venn et al. 2004
Stellar Abundances in the Milky Way

compilation by Venn et al. 2004

“The Knee”
Production factors of SNII


Woosley & Weaver 1995
Production factors of SNII


The indicated elements is given in the key in the upper right.
EMPS in Galactic halo

ESO Large Programme:
“The First Stars”

30 giants:

$-4.1 < [\text{Fe/H}] < -2.7$

Cayrel et al. 2004
The most ancient object we know of?

[Fe/H] = -5.4

Spectra of Stars with Different Metal Content

The Very Metal-Deficient Star HE 0107-5240
Dwarf Galaxies
Only the very closest galaxies can be subjects of detailed abundance studies of old (RGB) stars: mostly dSph
Metallicity Indicator

CaII Triplet $R \sim 6000$

Only valid for RGB stars!!

Hurley-Keller D., Mateo M., Grebel E.K., Apj, 523, 25
Detailed Abundances

Fe 80, 20
O 2
Na 5 Cu 2
Mg 3 Zn 1
Al 2 Y 4
Si 5 Ba 3
Ca 9 Nd 2
Sc 1 La 3
Ti 9, 6 Eu 1
Cr 2
Mn 6
Co 2
Ni 3

Metallicity Indicators
Global Properties

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
Global Metallicity Correlation

Do Galactic halo & dSph metallicity distributions differ significantly?

Metallicity Distribution

Ca II triplet calibration...

Extra points from analyses by Shetrone with HET (Draco & Umin), Venn with Magellan (Car)

Only valid for RGB stars!!

The slope has to change or the relation will become unphysical around $[\text{Fe/H}] \sim -3$
Modelling the CaT

Globular cluster stars of “known” metallicity (from HR spectroscopy) compared to CaT line widths

Starkenburg et al. 2009
Modelling the CaT
Modelling the CaT

Tafelmeyer et al. 2010
Aoki, halo stars priv. comm. Norris et al. 2007 (Boo)
X-shooter commissioning data

Model vs. Data

Model points

Starkenburg et al. 2010
Modelling the CaT

Stars near the TRGB are the last to leave the correlation

Model points

Model vs. Data

Tafelmeyer et al. 2010
Aoki, halo stars priv.
comm. Norris et al. 2007 (Boo)
X-shooter comissioning data

Starkenburg et al. 2010
CaII triplet accuracy at low metallicity

Based on synthetic spectra can re-determine the CaT calibration at low [Fe/H]
Testing the New Calibration

Tafelmeyer et al. 2010
Venn et al. 2011 in prep
Aoki et al. 2009 A&A
Battaglia et al. 2008

Starkenburg et al. 2010
Call triplet metallicity indicator

Starkenburg et al. 2010
Metal Poor stars...

**Starkenburg et al. 2010**

![Graph showing the distribution of stars with metallicity](image1)

**Salvadori, Schneider & Ferrara 2007**

- $Z_{cr} = 10^{-4}Z_\odot$
- $Z_{cr} = 10^{-6}Z_\odot$
- $Z_{cr} = 0$

**Universal Salpeter IMF**

![Graph showing the distribution with the Universal Salpeter IMF](image2)
Detailed Abundances
α-element abundances in dSph

\[ M_v = -13.2 \quad -11.2 \quad -13.4 \quad -9.3 \quad -20.9 \]

```
[Fe/H]  -2  -1  0
M_v = -13.2 -11.2 -13.4 -9.3 -20.9
Fornax  Sculptor  Sagittarius  Carina  MW
```

“The Knee”

Hill et al. 2010
Letarte et al. 2010
Koch et al. 2008
Venn et al. 2011
Sbordone et al. 2007

Tolstoy, Hill & Tosi 2009

Figure 1  A schematic diagram of the trend of α-element abundance with metallicity. Increased initial mass function and star formation rate offset the trend in the directions indicated. The knee.
Extremely Metal Poor stars: clues to formation

Tafelmeyer et al. 2010
Shetrone et al. 2001, 2003
Frebel et al. 2010
Koch et al. 2008
Aoki et al. 2009
Letarte et al. 2010
Hill et al. 2011
heavy elements

Sculptor dSph
Hill et al. 2011, in prep
Tolstoy, Hill & Tosi 2009

Fornax dSph
Letarte et al. 2010

Large Magellanic Cloud
Pompeia et al. 2008
Evolved stars in CMDs

Groenewegen et al. 2009

Gullieuszik et al. 2007

Cioni et al. 2006
Age - Metallicity

LMC: Pagel & Tautvaisiene 1998 MNRAS

Scl: de Boer et al., in prep

Fnx: Battaglia et al. 2006 A&A
signatures of formation & evolution?

Based on Kormendy 1985; Binggeli 1994
see also Belokurov et al. 2007

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
signatures of formation & evolution?

Can we explain these diagrams?

based on Kormendy 1985; Binggeli 1994
see also Belokurov et al. 2007

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371
Conclusions

dSph contain stars with \([\text{Fe/H}] < -3\) (one has now been found at \([\text{Fe/H}] = -4\) !)

dSph, dI & Ufds show consistent abundance patterns

**Most** stars in dwarf galaxies are different from those in the Milky Way (!)

All dwarf galaxies (with the exception of M32) seem to follow a continuum of properties **suggesting** a common progenitor/formation & evolution processes which is still apparent even when all the gas has been removed.

This relation likely indicates the ability of galaxies of increasing mass to be increasingly stable against disruption from either surrounding galaxies or their own star formation processes (test: changing position of “knee” in alpha-elements). But they are still subject to variety of evolutionary influences....
Thanks to...

Nobuo Arimoto
Wako Aoki
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Giuseppina Battaglia
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Thomas de Boer
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Giuliana Fiorentino
Stefania Salvadori
Abhijit Saha
Monica Tosi
Matthew Shetrone
Kim Venn
Amina Helmi
Kozo Sadakane
Galactic Outflows (& Infall?)

NGC1569: Martin et al. 2002

Gas circulation!

Angleseretti et al. (2005)

Angeretti et al. (2005)

SFR (10^3 M_☉ year⁻¹ kpc⁻²)

NGC 1569

Look-back time

redshift

NGC 1569

Unobscured Northern X-Ray Lobe

Obscured Northern X-Ray Lobe

Observer Sightline

Unobscured Southern X-Ray Lobe

NGC 1569 HI Disk

Age (Gyr)

0 5 10 15 20 25 30 35 40 45 50

now
99% of the mass of the human body is made up of the six elements: oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus.
Where did it all come from?

- hydrogen (in water) — Big Bang (17 minutes)

- oxygen, carbon, nitrogen, calcium, phosphorous, sulphur, potassium, sodium etc. — gradual (millions to billions of years) fusion reactions in stars: spread by planetary nebulae and supernovæ

- iron — supernovæ: creation and distribution
The Local Group
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