The Physics of Galaxies

Observations versus Theory

From the Early Universe to the Present

Part 2

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Modeling the Formation & Evolution of Galaxies

Spectral — Bruzual '83ff

Observational relations

Chemical — Tinsley '68ff

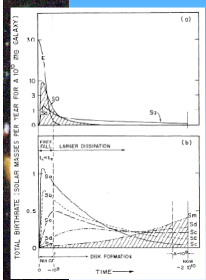
Dynamical — Toomre '72ff

Originally modeled one by one independently.
Now attempting to couple consistently : **GALEV models***

S : formation & evolution of stars +/- gas +/- dust
C : formation & nucleosynthesis of stars; infall/outflow of gas
D : internal & external gravitation, stars + gas + DM

*2003 Hertha-Sponer Research award DPG

Chemical & Spectral Evolution of a Galaxy
GALEV



Simplified parameterisations :

SFR (E) ~ exp (-t/1 Gyr)

SFR (Sp) ~ a · G(t)/M

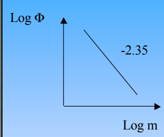
with efficiency parameter a chosen as to yield characteristic timescales for SF t* increasing from 2 Gyr for S0 through 13 Gyr (SFR ~ const.) for Sd

(SFR(t*) = 1/e SFR(t=0))

(Sandage 1986)

Spectral evolution :
- ➜ Stellar Initial Mass Function (Salpeter 1955, Kroupa+ 1993ff)
- ➜ Stellar evolutionary tracks, lifetimes, spectra
- ➜ Star Formation History of the galaxy

Chemical & Spectral Evolution of a Galaxy
GALEV



Normalisation :

$\int_{m_l}^{m_{up}} m\,\Phi(m)\,dm = 1$

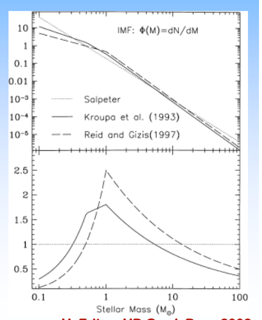
m_l : hydrogen burning limit
m_{up} : ~120 - 140 $M_\odot$

Stellar population :
- ➜ Stellar Initial Mass Function (Salpeter 1955, Kroupa+ 1993ff)
- ➜ Stellar evolutionary tracks, lifetimes, yields
- ➜ Star Formation History of the galaxy

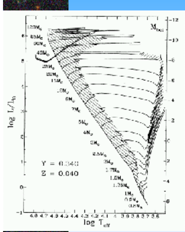
Chemical Evolution of Galaxies

IMF normalisation ➜ IMFs with flatter slopes have
- ☛ more low-mass stars : lock up chem. elements
- ☛ fewer high-mass stars : important for enrichment

IMF : little impact on optical colours, more on UV & emission lines, much on chem. evolution !



Stars evolve, die & produce new chemical elements -- depending on their initial mass & chemical composition



Stellar lifetimes & yields depend on chemical composition. E.g.

lifetimes:

Z=0.020 $\tau(1\,M_\odot) \sim 10\times10^9$ yr, $\tau(100\,M_\odot) \sim 2\times10^6$ yr

Z=0.004 $\tau(1\,M_\odot) \sim 7\times10^9$ yr, $\tau(100\,M_\odot) \sim 3\times10^6$ yr

Stellar population :
- ➜ Stellar Initial Mass Function
- ➜ Stellar evol. tracks, lifetimes (m, Z) & yields (m, Z)
- ➜ Star Formation History of the galaxy

Stellar Yields

Stars fusion heavy elements in their nuclei & set free part of them to the ISM/gas at (shortly before) the end of their lives (onion shell scheme)

$m_\star < 8\ M_\odot$: PN : H, He, C, N, O
$m_\star > 8\ M_\odot$: winds : H, He, C, N, O
SNII : -- " -- + Ne, Mg, Si, Ar, Ca, . . . , Fe, Ni

binary stars (appropriate mass ratio & orbit) :
SNIa : 0.6 $M_\odot$ Fe

timescales : PN, SNIa : $\sim 10^9 \ldots \sim 10^{10}$ yr
winds, SNII : $\sim 10^5 \ldots \sim 10^7$ yr

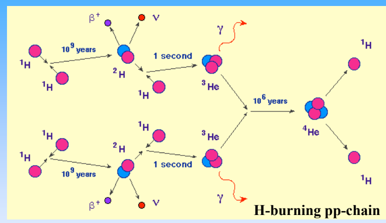
yields (winds, SNII) : metallicity dependent

$\dot{M}_{wind} \sim Z^4$

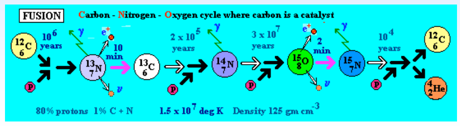
Stellar Nucleosynthesis

H burning :

pp-chain



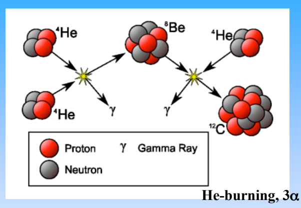
CNO cycle w. C as a catalyst



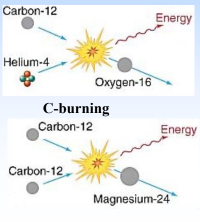
Stellar Nucleosynthesis

He burning : ^{12}C

triple α



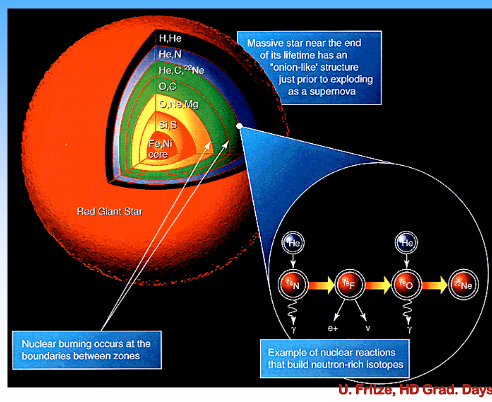
C burning : ^{16}O, ^{24}Mg



. . .

Si burning = last fusion process with energy production

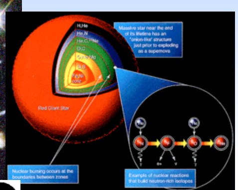
Stellar Nucleosynthesis : Onion shell structure of a massive star



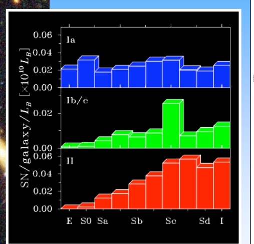
Chemical Evolution of Galaxies

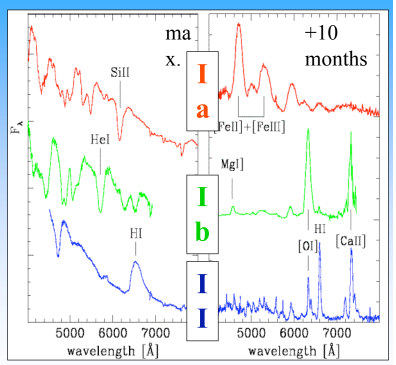
Type II SNe arise from the core collapse of massive stars (m = 8 - 40 $M_\odot$) and produce mainly alpha-elements (O, Mg, Si, Ca...) and some Fe, leave neutron star remnant

Stars more massive (m > 40 $M_\odot$) can end up as Type Ib/c SNe, leave neutron star, or black hole ?



Basic SN types and rates





(adopted from Matteucci 07)

Chemical Evolution of Galaxies

Type Ia SNe :

Single-degenerate scenario (Whelan & Iben 1974):

Binary system : 2 stars with m < 8 $M_\odot$

primary becomes C-O white dwarf

secondary becomes RG : fills its Roche lobe,

mass flows onto the WD, drives it towards the Chandrasekhar limit: primary explodes by C-deflagration & produces 0.6 $M_\odot$Fe

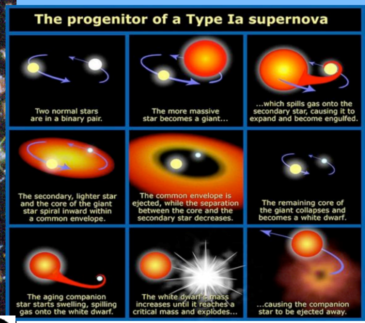
+ traces of other elements from C to Si

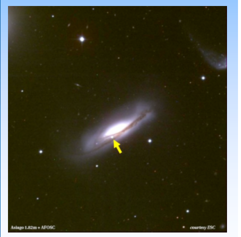
Clock for SNIa: lifetime of secondary : ≥ 1 Gyr !

Chemical Evolution of Galaxies

Type Ia SNe :

Single-degenerate scenario (Whelan & Iben 1974):





Nucleosynthesis : summary

During the Big Bang light elements are formed :

H, D, ^{3}He, ^{4}He, ^{7}Li

Spallation process in the ISM produces ^{6}Li, Be and B

Type II SNe produce α-elements (O, Ne, Mg, S, S, Ca), some Fe, light s- and r-process elements

Type Ia SNe produce mainly Fe and Fe-peak elements + some traces of elements from C to Si

Low and intermediate mass stars produce ^{4}He, C, N, s-process (A>90)

Deuterium is only destroyed to produce ^{3}He (which then also gets destroyed)

Chemical Abundances

Definitions :

mass fraction (all elements >H, He) =: metallicity Z

solar metallicity (photospheric abundances) $Z_\odot$ ~ 0.02

gas metallicities/abundances:

HII regions : O – abundance : R23 method, from emission lines

HI neutral gas : from HI absorption lines (physical & chem. parameters !)

given in terms of 12 + log (O/H) number ratios rel. to H

$Z_\odot$ ~ 0.02 ↔ 12+log (O/H) = 8.9

1/10 $Z_\odot$ ~ 0.002 ↔ 12+log (O/H) = 7.9

solar abundances not easy to determine & ≠ meteoritic abund.

Anders & Grevesse 89, Grevesse+96, Asplund+05, . . .

Solar Abundances

(Asplund+05)

Table 1. Element abundances in the present-day solar photosphere and in meteorites (C1 chondrites). Indirect solar estimates are marked with [..]

	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.25 ± 0.05	44	Ru	1.84 ± 0.07	1.77 ± 0.08
2	He	[10.93 ± 0.01]	1.29	45	Rh	1.12 ± 0.12	1.07 ± 0.02
3	Li	1.05 ± 0.10	3.25 ± 0.06	46	Pd	1.69 ± 0.04	1.67 ± 0.02
4	Be	1.38 ± 0.09	1.38 ± 0.08	47	Ag	0.94 ± 0.24	1.20 ± 0.06
5	B	2.70 ± 0.20	2.75 ± 0.04	48	Cd	1.77 ± 0.11	1.71 ± 0.03
6	C	8.39 ± 0.05	7.40 ± 0.06	49	In	1.60 ± 0.20	0.80 ± 0.03
7	N	7.78 ± 0.06	6.25 ± 0.07	50	Sn	2.00 ± 0.30	2.08 ± 0.04
8	O	8.66 ± 0.05	8.39 ± 0.02	51	Sb	1.00 ± 0.30	1.03 ± 0.07
9	F	4.56 ± 0.30	4.43 ± 0.06	52	Te		2.19 ± 0.04
10	Ne	[7.84 ± 0.06]	-1.06	53	I		1.51 ± 0.12
11	Na	6.17 ± 0.04	6.27 ± 0.03	54	Xe	[2.27 ± 0.02]	-1.97
12	Mg	7.53 ± 0.09	7.53 ± 0.03	55	Cs		1.07 ± 0.03
13	Al	6.37 ± 0.06	6.43 ± 0.02	56	Ba	2.17 ± 0.07	2.16 ± 0.03
14	Si	7.51 ± 0.04	7.51 ± 0.02	57	La	1.13 ± 0.05	1.15 ± 0.06
15	P	5.36 ± 0.04	5.40 ± 0.04	58	Ce	1.58 ± 0.09	1.58 ± 0.02
16	S	7.14 ± 0.05	7.16 ± 0.04	59	Pr	0.71 ± 0.08	0.75 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.45 ± 0.05	1.43 ± 0.03
18	Ar	[6.18 ± 0.08]	-0.45	62	Sm	1.01 ± 0.06	0.92 ± 0.04
19	K	5.08 ± 0.07	5.06 ± 0.05	63	Eu	0.52 ± 0.06	0.49 ± 0.04
20	Ca	6.31 ± 0.04	6.29 ± 0.03	64	Gd	1.12 ± 0.04	1.03 ± 0.02
21	Sc	3.05 ± 0.08	3.04 ± 0.04	65	Tb	0.28 ± 0.30	0.28 ± 0.03
22	Ti	4.90 ± 0.06	4.89 ± 0.03	66	Dy	1.14 ± 0.08	1.10 ± 0.04
23	V	4.00 ± 0.02	3.97 ± 0.03	67	Ho	0.51 ± 0.10	0.46 ± 0.02
24	Cr	5.64 ± 0.10	5.63 ± 0.05	68	Er	0.93 ± 0.06	0.92 ± 0.03
25	Mn	5.39 ± 0.03	5.47 ± 0.03	69	Tm	0.00 ± 0.15	0.08 ± 0.06
26	Fe	7.45 ± 0.05	7.45 ± 0.03	70	Yb	1.08 ± 0.15	0.91 ± 0.03
27	Co	4.92 ± 0.08	4.86 ± 0.03	71	Lu	0.06 ± 0.10	0.06 ± 0.06
28	Ni	6.23 ± 0.04	6.19 ± 0.03	72	Hf	0.88 ± 0.08	0.74 ± 0.04
29	Cu	4.21 ± 0.04	4.23 ± 0.06	73	Ta		-0.17 ± 0.03
30	Zn	4.60 ± 0.03	4.61 ± 0.04	74	W	1.11 ± 0.15	0.62 ± 0.03
31	Ga	2.88 ± 0.10	3.07 ± 0.06	75	Re		0.23 ± 0.04
32	Ge	3.58 ± 0.05	3.59 ± 0.05	76	Os	1.45 ± 0.10	1.34 ± 0.03
33	As		2.29 ± 0.05	77	Ir	1.38 ± 0.05	1.32 ± 0.03
34	Se		3.33 ± 0.04	78	Pt		1.64 ± 0.03
35	Br		2.56 ± 0.09	79	Au	1.01 ± 0.15	0.80 ± 0.06
36	Kr	[3.28 ± 0.08]	-2.27	80	Hg		1.13 ± 0.18
37	Rb	2.60 ± 0.15	2.33 ± 0.06	81	Tl	0.90 ± 0.20	0.78 ± 0.04
38	Sr	2.92 ± 0.05	2.88 ± 0.04	82	Pb	2.00 ± 0.06	2.02 ± 0.04
39	Y	2.21 ± 0.02	2.17 ± 0.04	83	Bi		0.65 ± 0.03
40	Zr	2.59 ± 0.04	2.57 ± 0.02	90	Th		0.06 ± 0.04
41	Nb	1.42 ± 0.06	1.39 ± 0.03	92	U	<-0.47	-0.52 ± 0.04
42	Mo	1.92 ± 0.05	1.96 ± 0.04				

Chemical Evolution of Galaxies

Basic principles

- ☆ Initial conditions (gas cloud with all or part of present mass)
- ☆ Initial abundances (Big Bang or Pop3 pre-enrichment)
- ☆ IMF w. normalisation $\int_{ml}^{mup}\Phi(m)\, m\, dm = 1$ or = FVM (=0.5) (Bahcall+03)

  Salpeter 1955 $\Phi(m) \sim m^{\alpha}$, $\alpha = -2.35$

  Kroupa+03 : flatter below 1 $M_\odot$
- ☆ SFR(t) : spirals: SFR(t) := $\Psi(t) \sim (G(t) / M_{tot})$, G : gas mass
- ☆ Infall/outflow rates & abundances or closed box
- ☆ Stellar yields & lifetimes
- ☆ Assumption how to mix recycled and remaining gas
- ☆ Equations combining all this (B. Tinsley 1968ff)

Modeling the Chemical Evolution of Galaxies

Tinsley's equations :

(Beatrice Tinsley 1980, Fund. Cosmic Phys. 5, 287)

☆ $M_{tot} = M_{baryon} = G+S$ gas + stars

☆ $dG/dt = - \Psi + e\ (+ F - E)$ Ψ :SFR, F : inflow, E : outflow rate
☆ $dS/dt = + \Psi - e$ e : ejection rate from stars
all quatities =f(time)!

$e(t) = \int_{mt}^{mup} (m - m_{rem})\ \Psi(t - \tau_m)\ \Phi(m)\ dm$ Φ :IMF,
m_t : turn-off mass, m_{up} : upper mass limit (IMF)

☆ $d(GZ)/dt = + e_Z - Z \cdot \Psi + Z_F \cdot F - Z_E \cdot E$

$e_Z(t) = \int_{mt}^{mup} [(m - m_{rem})Z(t - \tau_m) + m\ p_Z(m)]\ \Psi(t - \tau_m)\ \Phi(m)\ dm$

$p_Z(m)$: newly produced yield of star with mass m
(mass fraction)

Modeling the Chemical Evolution of Galaxies

Abundance evolution of individual elements :

In analogy to global metallicity : $Z \rightarrow X_i$
i : H, He, C, N, O, Mg, Mn, Al, Si, S, Cr, Fe, Ni, Zn

$d(GX_i)/dt = + e_{Xi} - X_i \cdot \Psi + X_{iF} \cdot F - X_{iE} \cdot E$

$e_{Xi}(t) = \int_{mt}^{mup} [(m - m_{rem})X_i(t - \tau_m) + m p_{Xi}(m)]\ \Psi(t - \tau_m)\ \Phi(m)dm$

but split IMF in mass range 3 – 8 $M_\odot$ into fraction A of binaries giving rise to SNIa and fraction (1-A) of single stars or binaries that do not end as SNIa.

Use for SNIa binaries yields for SNIa (e.g. Nomoto+97ff, Thielemann+98)

$p_{Xi}(m)$: newly produced yield in element X_i of star with mass m
(mass fraction)

Modeling the Chemical Evolution of Galaxies

Equations :

G_i := mass fraction of gas in the form of element i

$$\dot{G}_i(t) = -\psi(r,t)X_i(r,t) + \int_{M_L}^{M_{Bm}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m$$
$$+A\int_{M_{Bm}}^{M_{BM}} \phi(M_B)\left[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})\mathrm{d}\mu\right]\mathrm{d}M_B$$
$$+(1-A)\int_{M_{Bm}}^{M_{BM}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m$$
$$+\int_{M_{BM}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m + X_{A_i}A(r,t). \quad (1)$$

Modeling the Chemical Evolution of Galaxies

Equations :

SNIa rate : (Matteucci & Greggio 83)

$$R_{SNeIa} = A\int_{M_{B_m}}^{M_{B_M}} \phi(M_B) \int_{\mu_m}^{0.5} f(\mu)\psi(t-\tau_{M_2})\mathrm{d}\mu\,\mathrm{d}M_B, \quad (3)$$

where M_2 is the mass of the secondary, M_B is the total mass of the binary system, $\mu = M_2/M_B$, $\mu_m = max\{M_2(t)/M_B, (M_B - 0.5M_{B_M})/M_B\}$, $M_{B_m} = 3\ M_\odot$, $M_{B_M} = 16\ M_\odot$. The IMF is represented by $\phi(M_B)$ and refers to the total mass of the binary system for the computation of the SNIa rate, $f(\mu)$ is the distribution function for the mass fraction of the secondary, $f(\mu) = 2^{1+\gamma}(1+\gamma)\mu^\gamma$, with $\gamma = 2$; $A = 0.05$ is the fraction of systems with total mass in the appropriate range, which give rise to SNIa events. This quantity is fixed by reproducing the observed SNe Ia rate at the present epoch (Cappellaro et al. 1999; see also Madau et al. 1998).

Modeling the Chemical Evolution of Galaxies

Assumption how to mix freshly enriched (hot) gas set free in stellar winds and SNe with rest :

Instantaneaous Recycling Approximation (IRA)
stars > 1 $M_\odot$ die instantaneously (~ wrong)
stars < 1 $M_\odot$ live forever (~ true)
➜ allows for analytical solution

Account for individual stellar lifetimes $\tau(m, Z)$
➜ numerical models

Returned mass fraction : m_t = turn-off mass = mass of star for which $\tau(m)=t$

$$R := \int_{mt}^{mup} (m - m_{rem})\Phi(m)\ dm$$

Chemical Evolution of Galaxies

Infall/outflow rates:

closed box : no infall/outflow
open systems : infall rate F(t)
const. in time or
~ exp(- t / τ) or even ~ exp(- t / τ (r))

outflow rate E(t)
~ SFR(t)

Infall abundances Z_F, X_{iF}: primordial (Big Bang or Pop3)
Outflow abundances Z_E, X_{iE}: ????
outflow triggered by stellar winds & SNe: hot & freshly enriched
outflows observed to entrain neutral material, how much ????

Closed box : simplest model, allows for analytical solution

Analytical Solution

Assumptions : ideal and instantaneous mixing
1 gas phase only

with closed box
Instantaneous Recycling Approximation
$Z(0)=0$, $G(0)=M_{tot}$

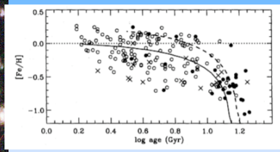
analytical solution :

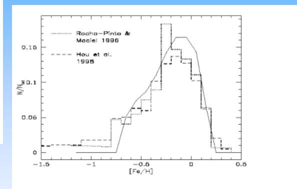
$Z(t) = - y \ln (G/M_{tot})$ y: total yield := mass ratio of newly produced heavy elements restored to ISM vs. locked up in stars

➜ metallicity increases as gas content decreases ✔

Modeling the Chemical Evolution of Galaxies

Observations :
☆ Age – metallicity relation of Milky Way stars





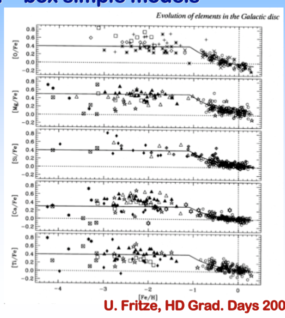
☆ G – dwarf problem in solar neighbourhood (& E gals)
(i.e. low number of very metal – poor stars)
☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars

not reproduced by closed – box simple models

Modelling the Chemical Evolution of Galaxies

Observations :
☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars
(Pagel & Tautvaisiene 95)

not reproduced by closed – box simple models



Modelling the Chemical Evolution of Galaxies

Observations :

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(i.e. low number of very metal – poor stars)

☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars

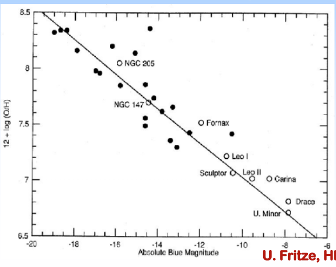
not reproduced by closed – box simple models

require
* infall or
* Pop3 or
* chemo – dynamical evolution or
* metallicity – dependent stellar yields
(chemically consistent chem. evol.)

Chemical Evolution of Dwarf Galaxies

Observations :
* Luminosity – metallicity relation for dwarf galaxies
(dEs & dIrrs on same scale !?)
(Skillman+89)

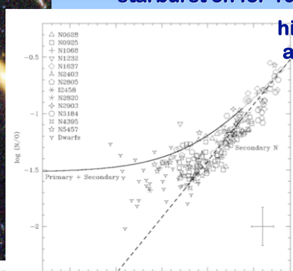
SFR(t) explains the light along with the metals,
i.e. reproduces the luminosity-metallicity relation



Chemical Evolution of Dwarf Galaxies

Observations :
* N/O vs O/H in SFing dwarf galaxies : big scatter in N/O at fixed O/H (van Zee+98)

explained by fluctuating SFRs / intermittent bursts
starburst on for 10^{5-6} yr, off for few 10^9 yr



high SFR/burst : O/H increases (SNII)
after burst : O/H decreases ,
N/O increases
(intermed. mass stars)

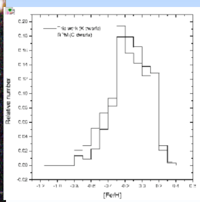
burst

after burst

Modelling the Chemical Evolution of Galaxies

* broad metallicity distribution of stars in solar neighb.
* broad metall. distrib. of stars (& GCs) in Elliptical gals

requires accounting for composite metallicity distribution of stars within galaxies
(chemically consistent evolutionary synthesis)

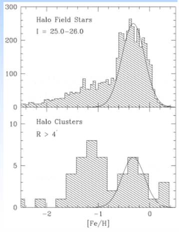


Metall. distribution of solar neighborhood stars
(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] > 2 dex

Metall. distribution of halo stars and GCs in NGC 5128

(Harris et al. 1999)



Chemically Consistent Chemical Evolution

Stellar yields at low Z differ significantly from $Z_\odot$ yields
--> stellar yield ratios [N/O], [C/O], [Mg/Fe], . . .
change with metallicity !

For elements with different nucleosynthetic origin,
ISM abundance ratios depend on SFH

SNII elements (O, Mg, Ca, ..., = α) vs.
intermediate stellar mass elements (C, N) vs.
SNIa elements (Fe, Ni, Zn,...)

➜ via the SFH, stellar evolution and galaxy evolution get intimately coupled !

In principle,

stellar evol. tracks/isochrones, yields, model atmospheres
are required for the full range of element ratios !!
(not available yet)

GALEV models use yields for 5 different (solar scaled) abundances

Chemically Consistent Chemical Evolution

Cosmological model (H_o, Ω_m, Ω_Λ, z_f) : time <-> redshift

$X_i(t)$ <-> $X_i(z)$

i : H, He, C, N, O, Mg, Mn, Al, Si, S, Cr, Fe, Ni, Zn

Redshift evolution of ISM abundances in spirals <--> Damped Lya Absorber abundances (Keck HIRES spectra)

DLAs contain bulk of baryonic matter at z ~ 2 . . . 3

⟨mass of gas in DLA⟩ ~ ⟨mass of stars + gas in local spiral⟩

? DLAs = (proto-) galactic disks ?

Chemically Consistent Chemical Evolution

Cosmological model (H_o, Ω_m, Ω_Λ, z_f) : time <-> redshift

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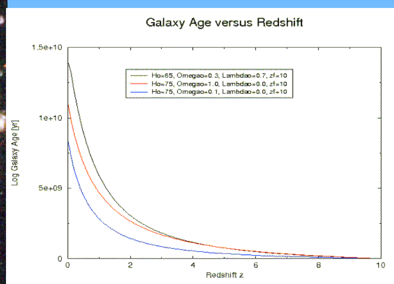


S, Cr, Fe, Ni, Zn

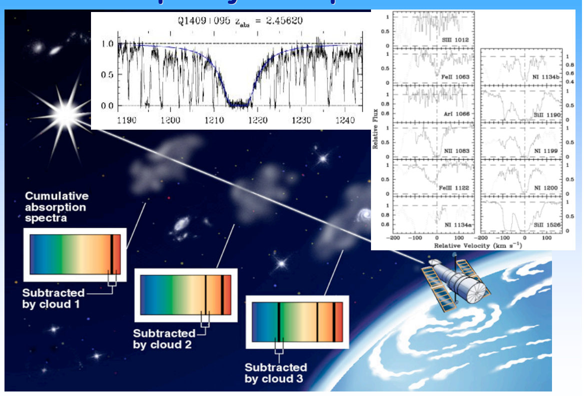
mped Lya Absorber abundances
eck HIRES spectra)

atter at z ~ 2 . . . 3

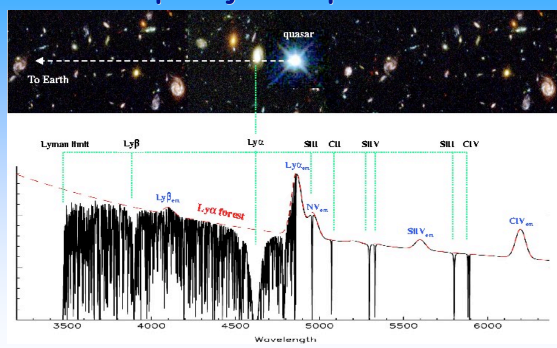
+ gas in local spiral⟩

? DLAs = (proto-) galactic disks ?

Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers



Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers



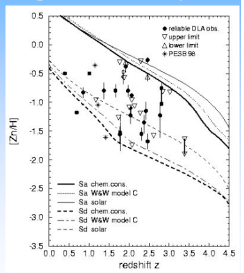
Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ CC spiral models explain redshift evolution of DLAs ✔
z~4 . . . . . z~0 (over > 90 % age of the Universe)

★ DLAs = spiral progenitors ✔
model abundances -> local HII abundances for z -> 0

★ change in the DLA galaxy population towards low z
gas poor & metal rich galaxies drop out of DLA sample

★ low luminosities of DLA galaxies
confirmed by many non-detections and few VLT detections



(Lindner, Fritze, Fricke 1999, Fritze, Lindner, Möller 1999)

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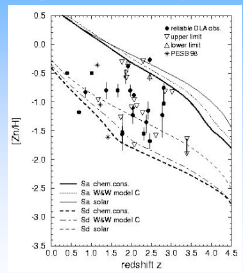

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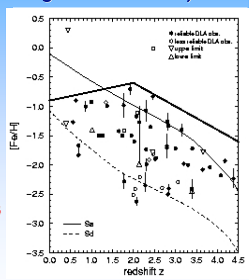

(Lindner, Fritze, Fricke 1999, Fritze, Lindner, Möller 1999)

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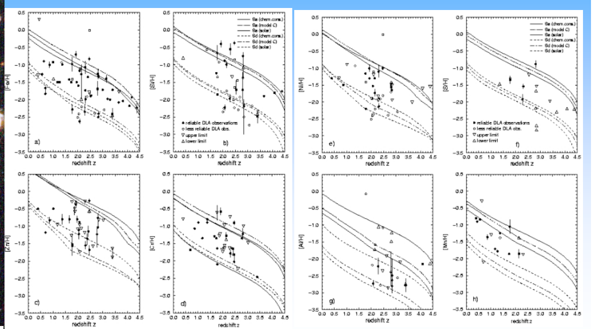
Chemically Consistent Chemical Evolution

(Lindner, FvA, Fricke 1999)

Spiral ISM abundances <--> DLA abundances



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Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ DLA = transition stage in the life of ~ all (spiral) galaxies

not much room for infall :

★ high masses of spiral galaxies @ z ~ 2 - 4 :

~ 50% of present M_{tot}, mostly gas

(Lindner+99, Fritze+99)

confirmed by HIRES kinematics (Prochaska & Wolfe 00ff) :

asymetric profiles of damped Lyα absorption line due to rotation with v_{rot} > 200 km/s ➜ M_{dyn} ~ 10^{11} $M_\odot$

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Chemically Consistent Chemical Evolution – Damped Ly

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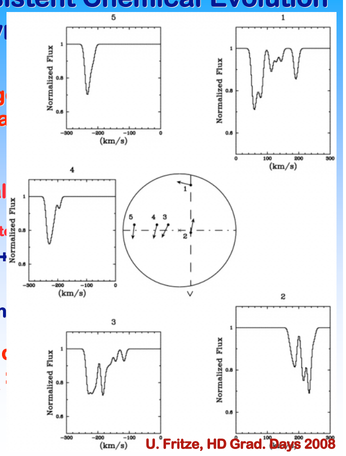

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Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ high masses of spiral galaxies @ z ~ 2 - 4 :

≥ 50% … ~ 100% of present M_{tot}, mostly gas

(Lindner+99, Fritze+99, Prochaska+00ff)

? how can this be ?

Hierarchical galaxy formation models predict merger trees & galaxies to have much lower masses at high redshifts.

Λ-CDM: bottom-up formation of structures

Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ high masses of spiral galaxies @ z ~ 2 - 4 :

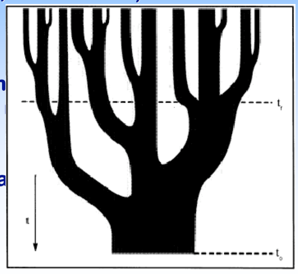
≥ 50% … ~ 100% of present M_{tot}, mostly gas

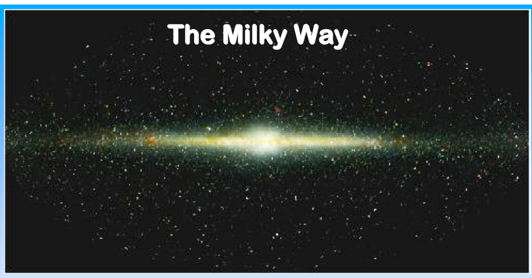
(Lindner+99, Fritze+99, Prochaska+00ff)

? how can this be ?

Hierarchical galaxy form
trees & galaxies to have
redshifts.

Λ-CDM: bottom-up forma





Sbc type galaxy. Structure : bulge, disk (thin/thick), halo

bulge: stars, star clusters,
the nuclear star cluster, BH ~ 3.6 10^6 $M_\odot$

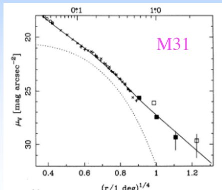
disk: gas, dust, young stars, HII regions,
young open star clusters

halo: field stars, Globular Clusters : all old and metal-poor,
diffuse gas (HI, HII, seen in absorption MgII, CIV
against background QSOs)

The Milky Way Bulge

The MW bulge is small & exponential, typical of later-type galaxies, unlike the large $r^{1/4}$ - bulge of M31.

It contains ~ 25% of the light



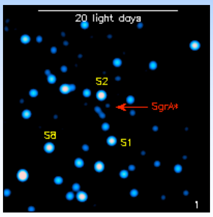
Pritchet & van den Bergh 1994

The Milky Way Bulge

NIR Adaptive Optics (Genzel & coll.) NAOS/CONICA @ VLT

Nuclear star cluster: thousands of young stars
within few light years of the Galactic Centre (GC)

☛ how can stars form
& survive there?



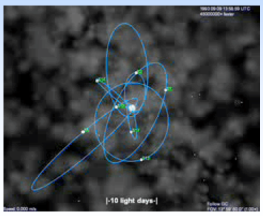
The Milky Way Bulge

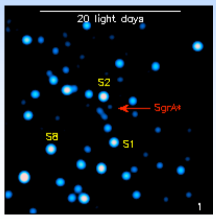
NIR Adaptive Optics (Genzel & coll.) NAOS/CONICA @ VLT

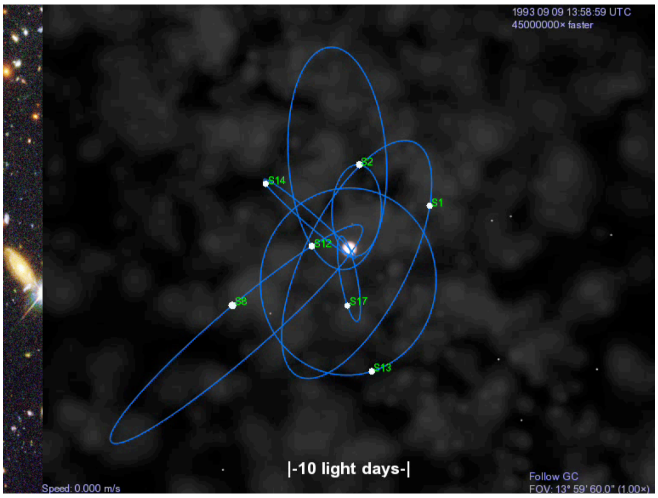
Nuclear star cluster: thousands of young stars
within few light years of the GC

☛ stellar motions : BH ~ 3.6 10^6 $M_\odot$

stars get as close to the BH as a few Schwarzschild radii,
flaring observed on AO NIR images -- accretion.

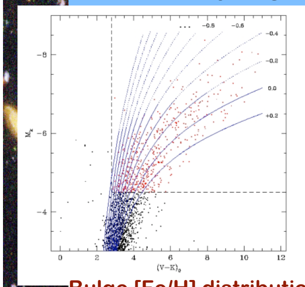




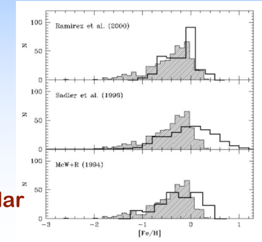


Ages and metallicities of the bulge stars

Zoccali et al 2003 : stellar photometry at
(l, b) = (0°.3, -6°.2) : old population > 10 Gyr.
No trace of younger population.



Extended metallicity distribution, from [Fe/H] = -1.8 to +0.2 (subsolar)



Bulge [Fe/H] distribution similar to solar neighbourhood (thin + thick disk)

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Formation of Bulges

Later type spirals (like the Milky Way) have small near-exponential boxy bulges (pseudo bulges).
Early type spirals have large $r^{1/4}$ bulges (true bulges).

(eg Courteau et al 1996)

Small exponential bulges are likely generated by disk instability : bar formation & destruction :

theory: eg Combes & Sanders 1981 ...
observations: eg Bureau & Freeman 1999 ...

Pseudo - bulges

(Kormendy & Kennicutt 04, ARA&A, Kormendy 07)

Big $r^{1/4}$ bulges (= true bulges) are likely formed by mergers or accretion.

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The Milky Way Bulge

The stars of the bulge are old and enhanced in α-elements [Mg/Fe]>0 $\Rightarrow$ rapid star formation history

In the disk instability scenario (bar formation - destruction - reformation), the structure of a pseudo-bulge may be younger than its stars, which were originally part of the inner disk.

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The Milky Way Bulge : Summary

The bulge is not a dominant feature of our Galaxy - only ~ 25% of the light.

The bulge is probably an evolutionary structure of the disk, rather than a feature of galaxy formation in the early universe : a pseudo - bulge.
Structure and kinematics (so far) can be understood as a product of disk instability.

The a-enhancement indicates that star formation in the inner disk/bulge region proceeded rapidly.

The bulge structure may be younger than its stars.

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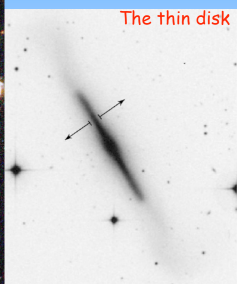
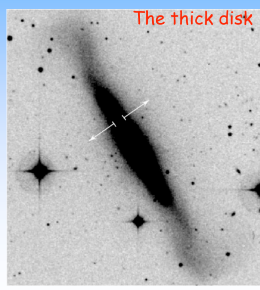
The Milky Way Thick Disk

Most spirals (including our Galaxy) have a second thicker disk component.
In some galaxies, it is easily seen :





NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980)

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The Milky Way Thick Disk

The Galactic thick disk is detected in star counts. Its larger scale height means its velocity dispersion is higher than for the thin disk.

The thick disk appears to be a discrete component, distinct from the thin disk.

Radial scale length = 3.5 to 4.5 kpc : uncertain

Scale height from star counts = 800 to 1200 pc (thin disk ~ 300 pc)

stellar density = 4 to 10% of the local thin disk

Near the sun, the Galactic thick disk is defined mainly by stars with [Fe/H] in the range -0.5 to -1.0, though its [Fe/H] distribution has a tail to very low [Fe/H] ~ -2.2.

Thick Disk : Summary

The thick disk formed rapidly and early (12 Gyr ago) by

☛ heating of the early thin disk in an epoch of merging which ended ~ 12 Gyr ago (eg Quinn & Goodman 1986)

or

☛ from early accretion of satellites, probably in mainly gaseous form (eg Brook et al 2004)

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Formation Scenario for the Milky Way Disk

Thin disk formation begins early @ z = 2 to 3.

Partly disrupted during merger epoch which heats it into thick disk observed now.

The rest of the gas then gradually settles to form the present thin disk

Not much is known about the radial extent of the thick disk. This is important, if the thick disk really is the heated early thin disk. Disks form from inside out, so the extent of the thick disk now would reflect the extent of the thin disk at the time of heating.

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The existence of a thin disk indicates that

- star formation did not start until the gas had settled to the disk plane
- since the onset of star formation in the disk, the disk has suffered no significant dynamical disturbance from internal or external sources

-- pure disk galaxies are not readily produced in ΛCDM simulations: too much merger activity

Only 1 pure thin disk galaxy is known:

-- NGC 4244, which is fairly isolated

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The Milky Way Halo

contains halo field stars, Globular Clusters (out to ~100 kpc) & low-density gas

M101

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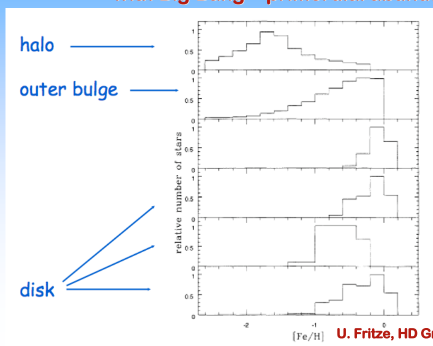
The Milky Way Halo

Stellar metallicity distribution extends to [Fe/H] = - 3.4

? where are the first stars with Big Bang = primordial abundances ?



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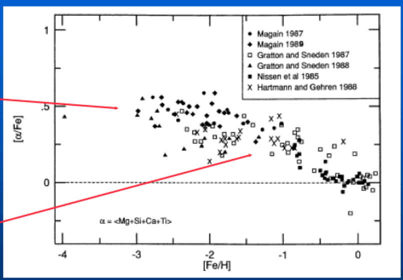
The Milky Way Halo

Stellar halo spherical ➜ SF faster than collapse
Enhanced [α/Fe] of metal-poor stars ➜ rapid halo SF

early core-collapse SNe (Type II, Ic) rich in O, α ejecta

after ~1 Gyr white dwarf binary SNe (Type Ia) begin to enrich more in Fe



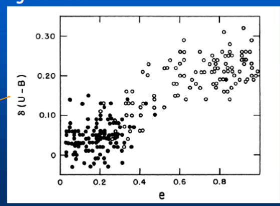
E. Grebel 2007 Wheeler, Sneden, Truran 1989, ARAA, 27, 279

The Milky Way Halo -- Formation

Eggen, Lynden-Bell, Sandage 1962 : UV excess of halo stars (~ measure of metallicity) correlated with orbital parameters (e.g. excentricity) ➜
monolithic collapse scenario for halo formation

- first clues come from in situ studies of halo stars in the solar neighborhood

UV excess metallicity index



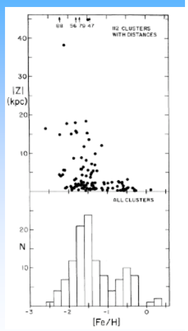
E. Grebel 2007 Eggen, Lynden-Bell, Sandage 1962, ApJ, 136, 748 ("ELS")

The Milky Way Halo -- Formation

Searle & Zinn (1985) : accretion scenario

GCs do not fit ELS scenario:
abundance-kinematic corr. due to disk-halo bimodality
Field stars :
abundance-kinematic corr. result of selection effects
thick disk confuses disk-halo separation

halo stars formed in protogalactic fragments & dwarf satellites, which were later accreted one by one
(Searle, Zinn1978, ApJ, 225, 357)

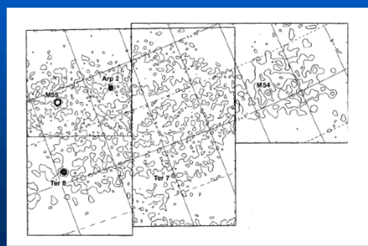


Zinn 1985, ApJ, 293, 424

The Milky Way Halo

Direct Evidence for Accretion

Sagittarius dwarf galaxy
- currently merging with Milky Way
- diameter >20 degrees, with larger tidal streamer
- L = 1-2 x 10^7 $L_\odot$
- M ~ 10^8 $M_\odot$
- includes 5 globular clusters



E. Grebel 2007 Ibata et al. 1997, AJ, 113, 634

Spectral Evolution of a Galaxy

Integrated light, no spatial resolution, no dynamics

Galaxy spectrum (t) = $\sum$ Stellar spectra + gas (em./abs.)
(1 - 200) *10^9 + dust (abs./ em.)

Stellar spectrum = black body
+ 50 million atomic & molecular lines

high mass stars : hot, bright + blue : UV - opt. short - lived
low mass stars : cool, faint + red : opt. - NIR long - lived

Stellar population :
➜ Stellar Initial Mass Function
➜ Stellar lifetimes & evolutionary tracks (mass, composition)
➜ Star Formation History of the galaxy

Z : Metallicity := Mass fractions of heavy elements (>H, He)
Sun : Z=0.02

All Evolutionary Synthesis Models

start from gas cloud and give
- Star Formation History (SFH) (= SFR(t))
- Stellar Initial Mass Function (IMF)

use data base of stellar input physics to calculate spectral evolution of the stellar component

GALEV models calculate the evolution of
- resolved stellar population (CMDs),
- integrated light (spectra, photometry, Lick indices)
- chemical abundances (gas and stars)

➔ Chemically Consistent Evolutionary Synthesis

coupled to a cosmological model: redshift evolution of
- spectra, luminosities, colours, emission / abs. lines
- gas content, gas abundances, SFR

GALEV Evolutionary Synthesis Models

Input physics : stars & gas :

Stellar evolutionary tracks / isochrones : all masses M_l ... M_{up}
Padova / Geneva

Stellar spectra & absorption features : all spectral types & luminosity classes & metallicities : model atmospheres
(Kurucz / Lejeune) & Lick indices

Gaseous emission : continuum & lines : HII regions

Stellar yields : PNe, SNII, SNIa: C, N, O, Mg, . . ., Fe, . . .

5 metallicities [Fe/H] = -1.7 . . . + 0.4

solar scaled abundances

all pieces of stellar input physics
depend significantly on metallicity
and so does the output !

GALEV Evolutionary Synthesis Models

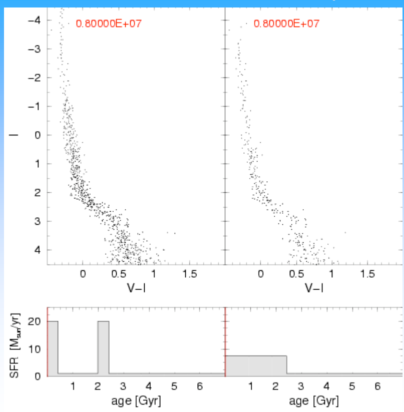
Output :

Time evolution of CMDs

Time & redshift evolution of

- Spectra 90 A ..... 160 μm
- Emission line strengths
- Luminosities UV ..... K Johnson, HST, Washington, Stroemgren, ...
- Colors
- Absorption features Mg2, Mgb, Fe5270, Fe5335, TiO1, TiO2, ...
- Galaxy masses: gas & stars, M/L
- ISM abundances → modified form of Tinsley's equations including SNIa (carbon deflagr. wd **)

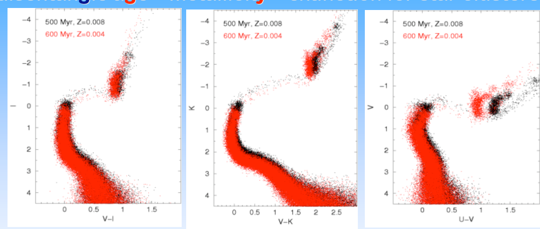
Evolution of Resolved Stellar Populations : CMDs(t)



run/stop:
click on
picture

Evolution of Resolved Stellar Populations : CMDs(t)

optimise observational strategies to
- disentangle age – metallicity – extinction for star clusters



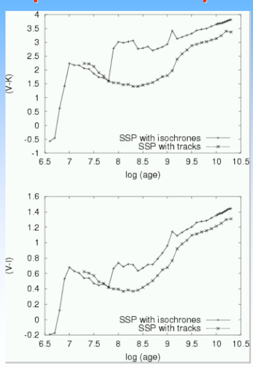
! long wavelength basis !

young (<3 Gyr) : U-band important for ages
old (>3 Gyr) : K-band for metallicities

- reveal different age/metallicity subpopulations in galaxies

Integrated Light : Simple Stellar Populations

Importance of complete sets of stellar tracks / isochrones :



with TP- AGB
without TP- AGB

Age dating from V-I without TP- AGB :
ages wrong by ≥ 50 %

e.g. V- I ~ 0.6 :
$Age|_{w/o\ TP\text{-}AGB}$ ~ 6.3 10^8 yr
$Age|_{TP\text{-}AGB}$ ~ 6.6 10^7 yr

(Schulz, FvA, Fricke 2002)

Gaseous Emission

Importance of gaseous emission at young ages

N_{Lyc} [1/s] (T_{eff}, $R_☆$) ionising flux
summed over all O-, B-stars

(Stroemgren spheres, case B recomb. Osterbrock)

Lines and continuous emission

$F(H_\beta)$ ~ N_{Lyc}

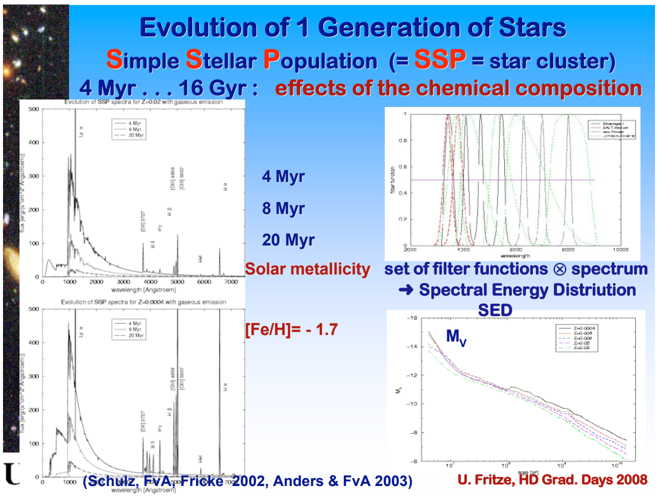
hydrogen line ratios : atomic physics

(Lyman, Balmer, Paschen, Brackett series)

heavy element line ratios : depend on metallicity, T_e, N_e

- from photoionisation models (radiation transport)
- from observations

Continuous emission ~ N_{Lyc} : atomic physics


Evolution of 1 Generation of Stars
Simple Stellar Population (= SSP = star cluster)
4 Myr . . . 16 Gyr : effects of the chemical composition
4 Myr
8 Myr
20 Myr
Solar metallicity
[Fe/H]= - 1.7
set of filter functions ⊗ spectrum
➜ Spectral Energy Distriution
SED
M_V
(Schulz, FvA, Fricke 2002, Anders & FvA 2003)
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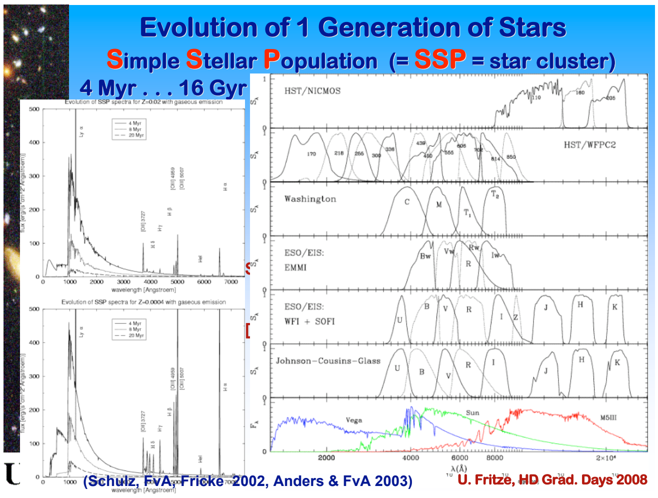
Evolution of 1 Generation of Stars
Simple Stellar Population (= SSP = star cluster)
4 Myr . . . 16 Gyr
HST/NICMOS
HST/WFPC2
Washington
ESO/EIS: EMMI
ESO/EIS: WFI + SOFI
Johnson−Cousins−Glass
Vega
Sun
(Schulz, FvA, Fricke 2002, Anders & FvA 2003)
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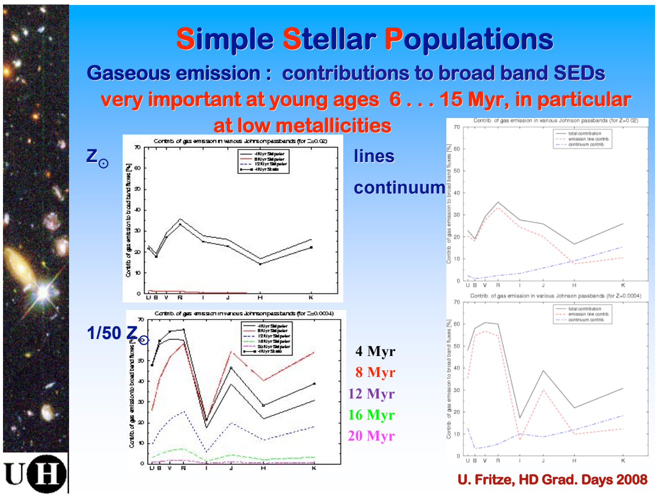
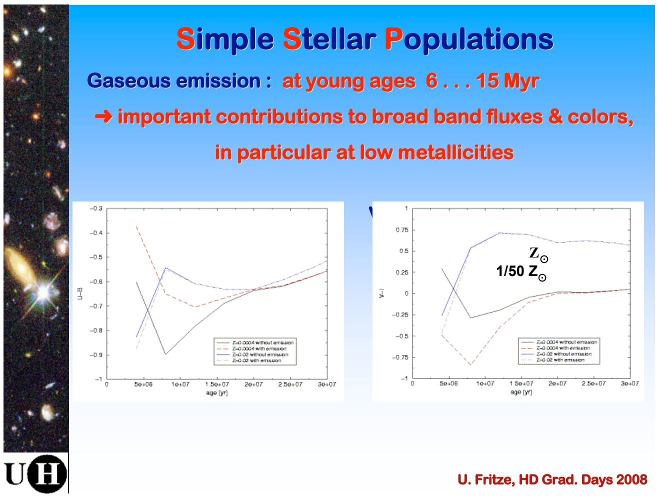
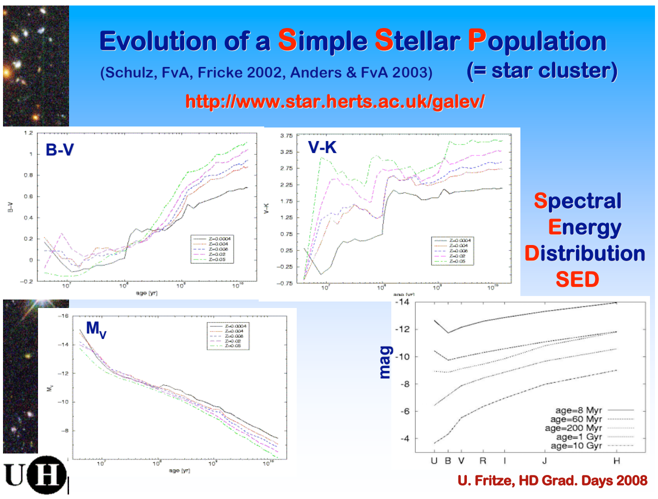
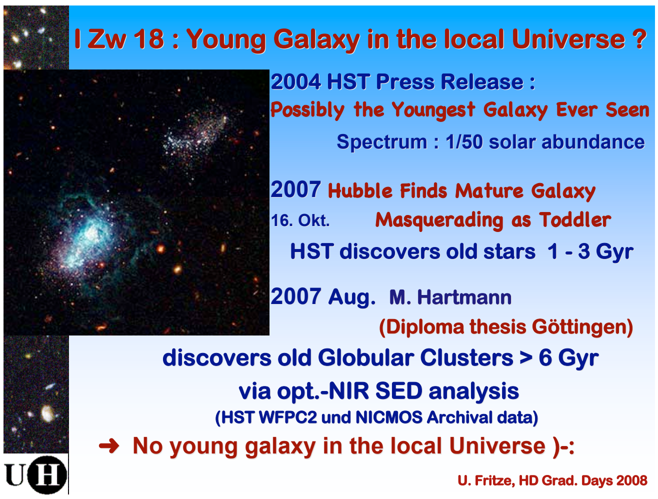

Simple Stellar Populations
Gaseous emission : contributions to broad band SEDs
very important at young ages 6 . . . 15 Myr, in particular
at low metallicities
$Z_\odot$
lines
continuum
1/50 $Z_\odot$
4 Myr
8 Myr
12 Myr
16 Myr
20 Myr
U. Fritze, HD Grad. Days 2008


Simple Stellar Populations
Gaseous emission : at young ages 6 . . . 15 Myr
➜ important contributions to broad band fluxes & colors,
in particular at low metallicities
$Z_\odot$
1/50 $Z_\odot$
U. Fritze, HD Grad. Days 2008


Evolution of a Simple Stellar Population
(Schulz, FvA, Fricke 2002, Anders & FvA 2003)
(= star cluster)
http://www.star.herts.ac.uk/galev/
B-V
V-K
Spectral
Energy
Distribution
SED
M_V
mag
age=8 Myr
age=60 Myr
age=200 Myr
age=1 Gyr
age=10 Gyr
U. Fritze, HD Grad. Days 2008


I Zw 18 : Young Galaxy in the local Universe ?
2004 HST Press Release :
Possibly the Youngest Galaxy Ever Seen
Spectrum : 1/50 solar abundance
2007 Hubble Finds Mature Galaxy
16. Okt. Masquerading as Toddler
HST discovers old stars 1 - 3 Gyr
2007 Aug. M. Hartmann
(Diploma thesis Göttingen)
discovers old Globular Clusters > 6 Gyr
via opt.-NIR SED analysis
(HST WFPC2 und NICMOS Archival data)
➜ No young galaxy in the local Universe)-:
U. Fritze, HD Grad. Days 2008

Spectral Evolution of a Galaxy : GALEV

Lick stellar absorption indices :

defined to be measurable on spectra with
realistic S/N
relatively low spectral evolution

measured on large number of MW stars (disk & halo)

H_α, H_β, H_γ, H_δ, Mgb, Mg2, NaD, Fe5335, Fe5270, TiO, . . .

as a function of T_{eff}, log g, [Fe/H]

caveat : extrapolations !!!!

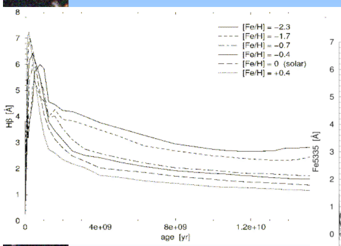
(Gorgas et al. 1993, Worthey 1994)

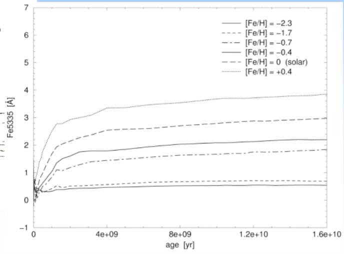
Evolution of a Simple Stellar Population

Time evolution & metallicity dependence of Lick stellar absorption indices

H_β age sensitive — but also metall. sensitive

Fe5335 metallicity sensitive — but also age sensitive !!!

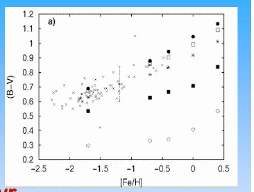




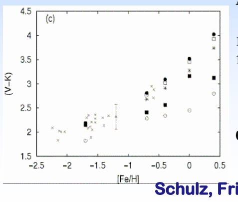
Star Cluster Colors <--> [Fe/H]

Empirical calibrations for MW GCs
(~ 12 Gyr, [Fe/H] £ - 0.5)

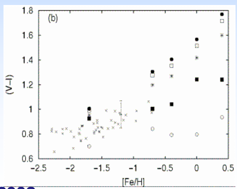
Theoretical calibrations from SSP models
- non-linear for [Fe/H] > - 0.5 *
- age dependent for ages < 12 Gyr



*spectr. confirmed by Kissler-Patig

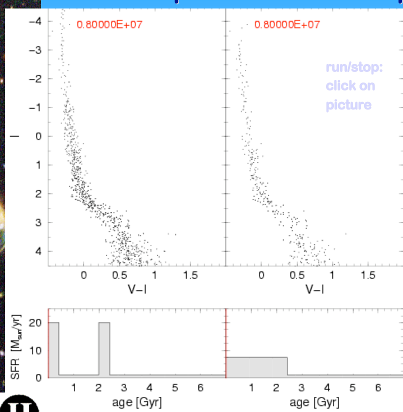


Ages
14 Gyr
10 Gyr
5 Gyr
1 Gyr
0.5 Gyr



Schulz, Fritze, Fricke 2002

Analysing the Resolved Stellar Populations of Local Group Galaxies from Deep HST - CMDs



Aims:
Star Formation
& Chemical Enrichment
Histories
SFHs & CEHs

The Local Group

> 43 galaxies (2007)

35 dwarfs:
17 dSphs, 5 dEs, 13 dIs

50% Local Group gals have M_{tot}<3 10^7 $M_\odot$ (dIs, dSphs)

van den Bergh 2000, PASP, 112, 529

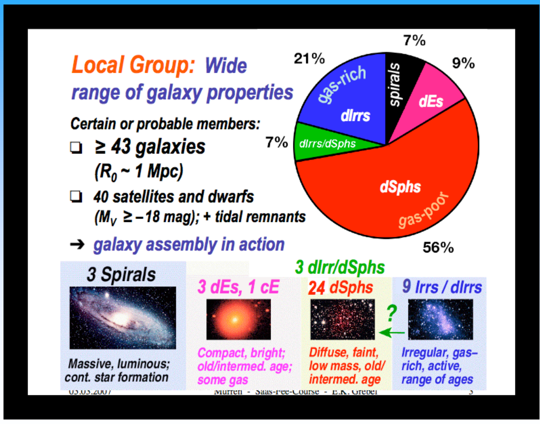
Data on Local Group Galaxies

Name	Alias	Type	M_V	D (Mpc) Galaxy	D (Mpc) Local Group
WLM	DDO 221	Ir IV–V	−14.4	0.95	0.81
IC 10	UGC 192	Ir IV:	−16.3	0.66	0.27
Cetus		dSph	−10.1	0.78	0.62
NGC 147	UGC 326	Sph	−15.1	0.66	0.22
And III	A0032+36	dSph	−10.2	0.76	0.31
NGC 185	UGC 396	Sph	−15.6	0.66	0.22
NGC 205	M110	Sph	−16.4	0.76	0.31
M32	NGC 221	E2	−16.5	0.76	0.31
M31	NGC 224	Sb I–II	−21.2	0.76	0.30
And I	A0043+37	dSph	−11.8	0.81	0.36
SMC		Ir IV/IV–V	−17.1	0.06	0.48
Sculptor		dSph	−9.8	0.09	0.44
Pisces	LGS 3	dIr/dSph	−10.4	0.81	0.42
IC 1613		Ir V	−15.3	0.72	0.47
And V		dSph	−9.1	0.81	0.37
And II		dSph	−11.8	0.68	0.26
M33	NGC 598	Sc II–III	−18.9	0.79	0.37
Phoenix		dIr/dSph	−9.8	0.40	0.59
Fornax		dSph	−13.1	0.14	0.45
LMC		Ir III–IV	−18.5	0.05	0.48
Carina		dSph	−9.4	0.10	0.51
Leo A	DDO 69	Ir V	−11.5	0.69	0.88
Leo I	Regulus	dSph	−11.9	0.25	0.61
Sextans		dSph	−9.5	0.09	0.51
Leo II	DDO 93	dSph	−10.1	0.21	0.57
Ursa Minor	DDO 199	dSph	−8.9	0.06	0.43
Draco	DDO 208	dSph	−8.6	0.08	0.43
Milky Way	Galaxy	S(B)bc I–II	−20.9:	0.01	0.46
Sagittarius		dSph(t)	−13.8::	0.03	0.46
SagDIG		Ir V	−12.0	1.18	1.29
NGC 6822		Ir IV–V	−16.0	0.50	0.67
Aquarius	DDO 210	V	−10.9	0.95	0.95
Tucanae		dSph	−9.6	0.87	1.10
Cassiopeia	And VII	dSph	−12.0	0.69	0.29
Pegasus	DDO 216	Ir V	−12.3	0.76	0.44
Pegasus II	And VI	dSph	−11.3	0.78	0.38

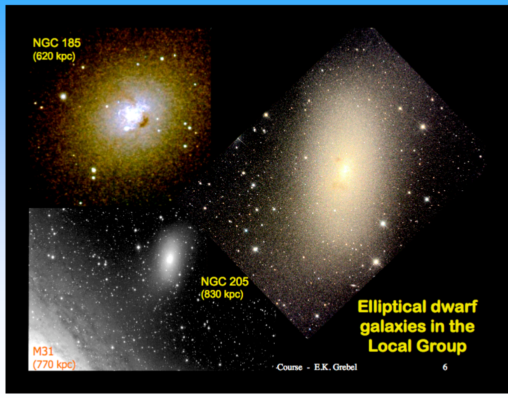
Note.—Galaxies are listed in order of increasing right ascension.

The Local Group

The Local Group (E. Grebel 2007, Saas-Fee Course)



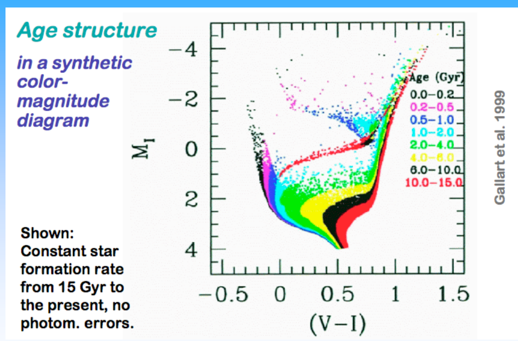
Dwarf Ellipticals



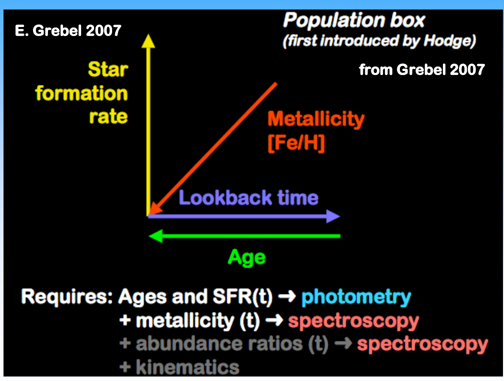
CMD Analyses of Local Group Galaxies

HST WFPC2 imaging
observational limit depends on distance D
detect Giant Branch & (upper) Main Sequence
stochastic effects (small star number statistics)
SF history entangled with chemical enrichment history
(and for dIs also with dust)

The SFHs of Dwarf Galaxies



The SFHs of Dwarf Galaxies

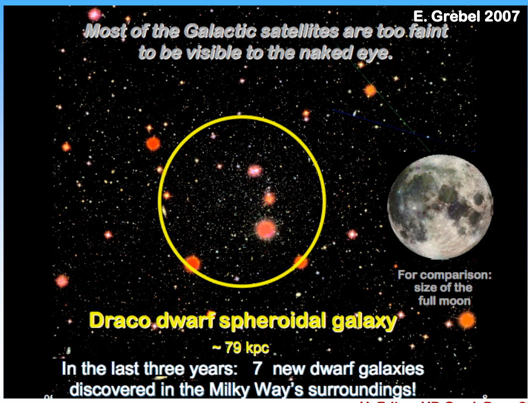


Dwarf Ellipticals

- ☆ spherical - elliptical, exponential light profiles
- ☆ high central stellar densities
- ☆ dEs and dE,Ns with nuclei containing up to 20% light
- ☆ $M_V \geq$ −17 mag, $\mu_V \leq 21$ mag arcsec^{-2}
- ☆ M(HI) ≤ 10^8 $M_\odot$, some still have ongoing low-level SF
- ☆ M_{tot} ~ 10^9 $M_\odot$
- ☆ long-lasting SF in the past
- ☆ considerable chem. enrichment
- ☆ in high galaxy density regions, mostly satellites

? Formation scenarios, progenitors, dEs -- dE,Ns, relation to other types of (dwarf) galaxies ?

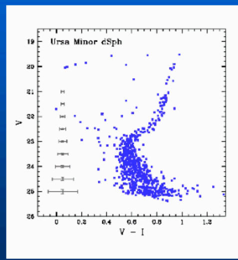
Dwarf Spheroidals



CMD Analysis of dSphs

Dwarf Spheroidal Galaxies

- SF history from HST CMDs
- young population is absent (by definition)
- old population ubiquitous
  - at least one purely old galaxy (Ursa Minor) -------->
- intermediate-age population varies from 0% --> >90%



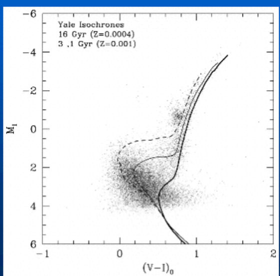
Mighell, Burke 1999, AJ, 118, 366

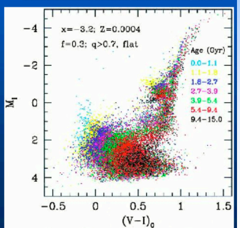
E. Grebel 2007

CMD Analysis of dSph

Leo I E. Grebel 2007

Relatively steady SF from 10-13 Gyr to ~1 Gyr ago



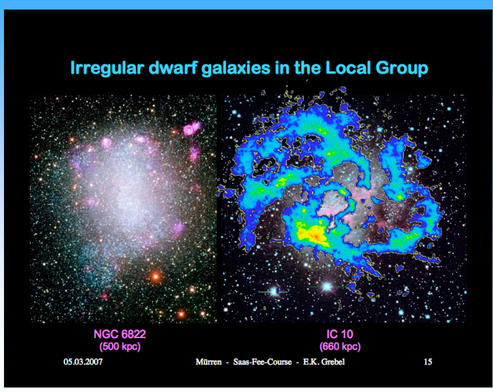


Gallart et al. 1999, ApJ, 514, 665 — Gallart et al. 1999, AJ, 118, 2245

Dwarf Spheroidals dSphs

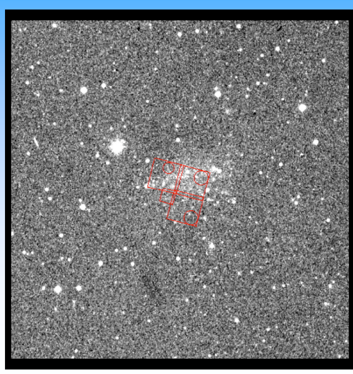
☆ diffuse, LSB dwarfs
☆ little central concentration
☆ younger stellar populations (more centrally concentr.)
☆ $M_V \geq -14$ mag, $\mu_V \geq 22$ mag arcsec^{-2} (least lum. gals known)
☆ M(HI) ≤ $10^5\ M_\odot$, no ongoing SF
☆ $M_{tot} \sim 10^7\ M_\odot$ (least massive gals known)
☆ exponential light profiles, $R_{1/2} > 100\ R_{1/2}$ (GCs@same lum.)
☆ long-lasting SF @ early times, all have old stellar pops
 some stopped SF 10 - 12 Gyr ago,
 some formed majority of their stars 6 - 8 Gyr ago
 few had SF 1 - 2 Gyr ago
 SF influenced by big companion
☆ low metallicities but large spread in abundances
☆ in high galaxy density regions, mostly satellites
☆ high DM fractions or radially varying veloc. dispersion anisotropy?

Dwarf Irregular Galaxies



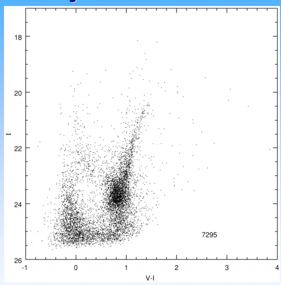
CMD Analyses of dIrrs

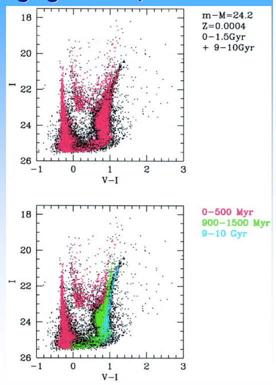
Tolstoy et al. 98: HST WFPC2 imaging of LeoA



CMD Analyses of dIs

Tolstoy et al. 98: HST WFPC2 imaging of LeoA, D=?



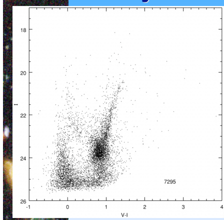


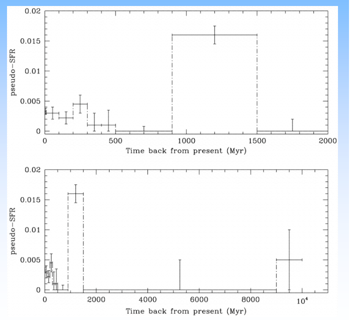
CMD Analyses of dIs

Tolstoy et al. 98: HST WFPC2 imaging of LeoA, BDM*=24.2 mag

12 + log (O/H) = 7.3 +/- 0.2 (2.4% solar)

(from Skillman+89, PNe)





SF history for lookback time ~2 Gyr

* BDM := m - M [mag]
bolometric distance modulus
m : apparent magnitude
M : absolute magnitude

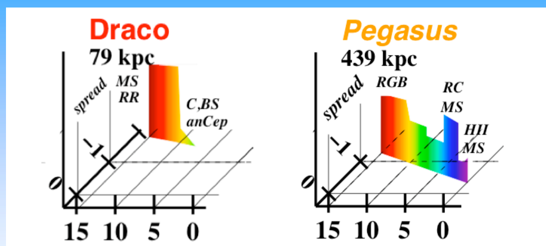
Dwarf Irregulars dIrrs, dIs

- ☆ blue, gas-rich, irregular, dominated by scattered HII regions
- ☆ young stellar populations, active SF
- ☆ $M_V \geq$ −14 mag, $\mu_V \leq$ 23 mag arcsec^{-2}
- ☆ M(HI) ≤ 10^9 $M_{\odot}$, clumpy, often more extended than stellar comp.
- ☆ M_{tot} ~ 10^{10} $M_{\odot}$
- ☆ stochastic SF, no spiral arms/density waves
- ☆ low metallicities but large spread in abundances ratios
- ☆ in low galaxy density regions
- ☆ do all dIrrs have old stellar populations ?

➜ if a dI stops SF, it will resemble a dSph after few 100 Myr

The SFHs of Dwarf Galaxies

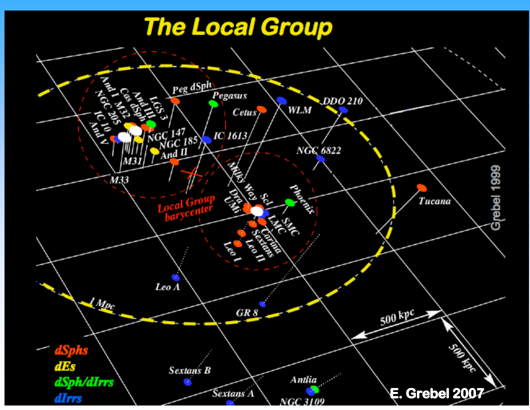
from Grebel 2007



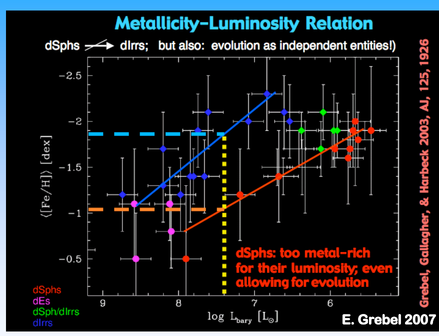
of a dSph of a dIrr

(Note: even within the same type, each dwarf has its own, unique star formation history; no two dwarfs are alike.) Grebel 1997

The Local Group



Dwarf Galaxies in the Local Group

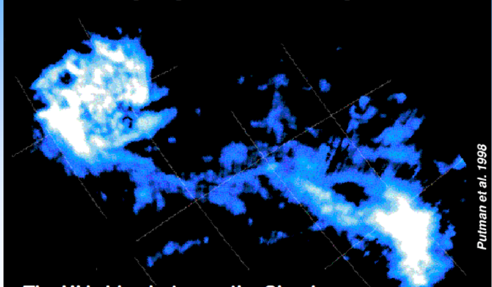


dSphs more massive before ? got shred down by tidal forces & past close passages to the MW or M31 ?

The LMC -- SMC -- Milky Way System

Interacting satellites: The Magellanic Clouds

The Magellanic Clouds interact with each other and with the Milky Way and will eventually be accreted.



The HI bridge between the Clouds:
Low-metallicity material with recent star formation

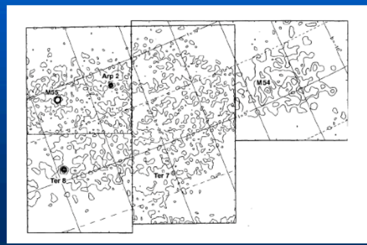
courtesy E. Grebel

The Milky Way Halo

Direct Evidence for Accretion

Sagittarius dwarf galaxy

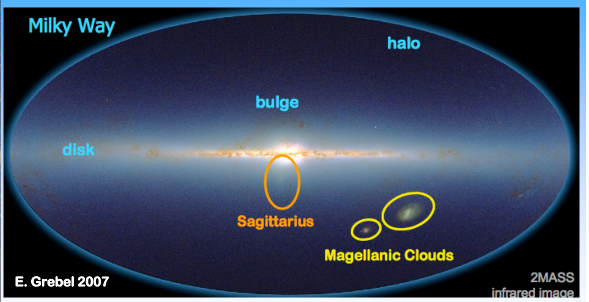
- currently merging with Milky Way
- diameter >20 degrees, with larger tidal streamer
- $L = 1\text{-}2 \times 10^7 L_\odot$
- $M \sim 10^8 M_\odot$
- includes 5 globular clusters



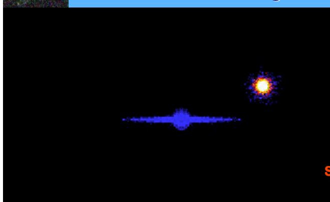
E. Grebel 2007

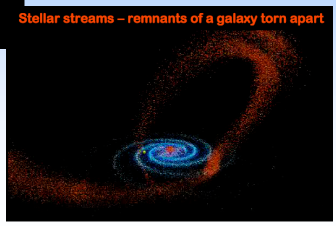
Ibata et al. 1997, AJ, 113, 634

The Milky Way System



Sag A : Disruption of a Satellite in the Milky Way Halo





More Satellites to the Milky Way ?

How many satellites has the Milky Way swallowed already ?
New streams are being discovered …

… how many are we still missing ?

RAVE (RAdial Velocity Experiment): 6dF spectrograph @ AAT
radial velocities to < 2 km/s for >300.000 stars (2003-10)
& chemical composition

Not enough to solve the missing satellite problem!

How faint/low mass can they go ?

Empty DM halos ?

More Satellites to the Milky Way ?

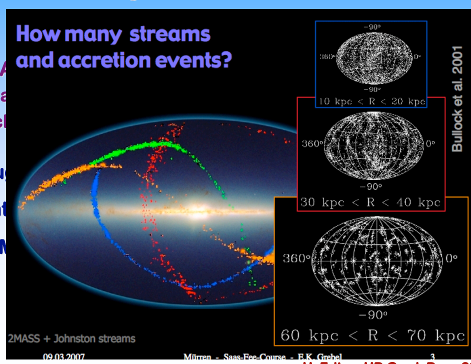
How many satellites has the Milky Way swallowed already ?
New streams are being discovered …

RAVE (RA… T
radia…
& c…

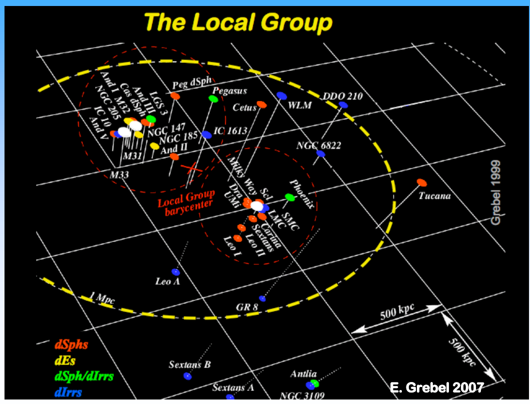
Not enou…

How faint…

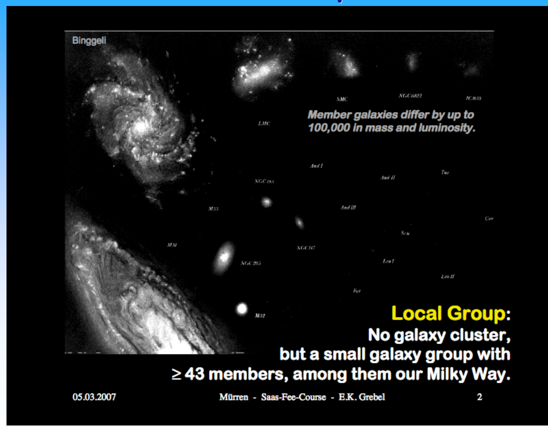
Empty D…



The Local Group



The Local Group



The Fate of the Local Group (Forbes+00)

= The elliptical galaxy formerly known as the Local Group

MW and M31 will probably merge in ~ 4 Gyr.

By that time they will have swallowed all their smaller comp., exhausted their gas, turned down their SF.

The young stellar pops will have faded: $M_V \leq -21$ mag.

➜ normal field elliptical

The Fate of the Local Group (Forbes+00)

The Globular Clusters will survive. [Gas-rich mergers may produce new GCs]

Collect all 700 Local Group GCs with their luminosities (incl. fading) & metallicities [Fe/H]

➜ ~ universal GC Luminosity Function

➜ ~ normal bimodal GC [Fe/H] distribution with peaks at [Fe/H] = -1.55 & -0.64

MP / MR = 2.5 / 1 MP metal-poor, MR metal-rich

➜ ~ normal GC specific frequency $S_N = N_{GC} \cdot 10^{0.4(MV+15)} \sim 3$

Local Group ➜ normal field elliptical, also in terms of GC population

The Fate of the Local Group (Forbes+00)

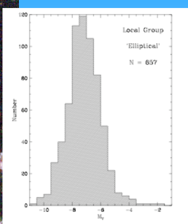


Fig. 1. Absolute magnitude distribution for the Local Group 'Elliptical'. The distribution resembles the 'universal' globular cluster luminosity function.

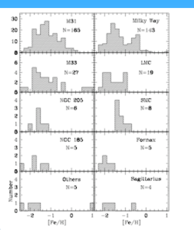


Fig. 2. Metallicities of Local Group globular clusters. The number of available globular clusters with individual measurements is indicated in each panel.

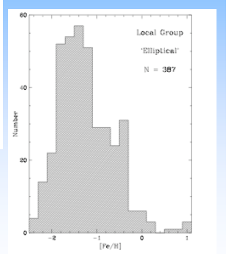


Fig. 3. Metallicity distribution for the Local Group 'elliptical'. The distribution reveals two peaks at [Fe/H] = -1.55 and -0.64.

Local Group merger
➜ normal field elliptical,
also in terms of its Globular Cluster System