Interacting Galaxies

Observations & Theory

Local Universe to High Redshift

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(Universität Göttingen)

SS 2008 Universität Göttingen

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Local Universe to High Redshift

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Dates:
17.4. Overview & basic concepts
(1.5. Holiday)
(15.5. HST Panel meeting)
22.5. Dyn. models & obs. examples
5.6. Star Bursts & Star Cluster Formation
19.6. ULIRGs & SCUBA galaxies
3.7. Galaxy transformation in clusters
17.7. Interactions @ high redshift

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Fundamental Questions about Galaxy Formation & Evolution

When and how did galaxies

- form their stars ? SFH (continuously – in starbursts)
- produce their heavy elements ? CEH (how much into ICM)
- assemble their masses ? MAH (stellar – gaseous)

How did all this depend on

- galaxy mass / type ?

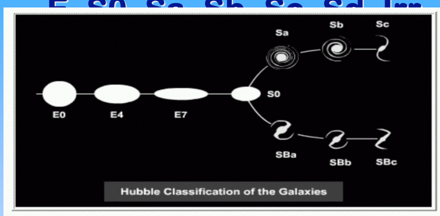
(down-sizing, staged galaxy formation)

- environment (field, group, cluster) ?

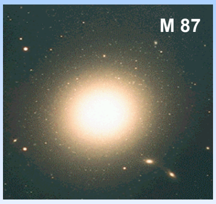
→ role of interactions, mergers, galaxy transformation?

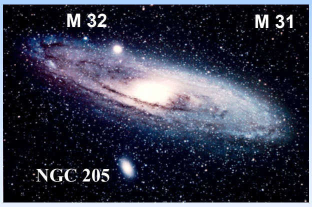
How is the formation & evolution of galaxies related to the formation & evolution of Large Scale Structure?

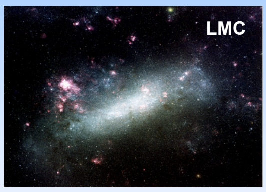
The Hubble Sequence of Normal Galaxies



(E. Hubble 1923ff)

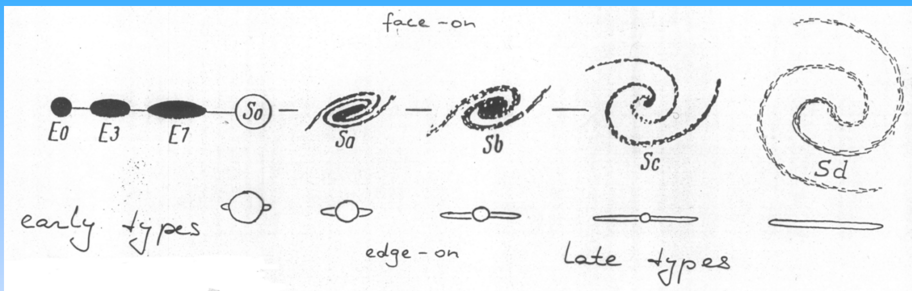






Beyond the Hubble sequence:
Dwarf galaxies : dE, dSph, dI
Low surface brightness galaxies : E, disk, dwarf
Starburst galaxies, interacting galaxies, radio gals, AGN, ULIRGs, SCUBA gals, Lyman Break Gals, . . .

The Hubble Sequence of Normal Galaxies



early type	late type galaxies
old stars	young + old stars
no/little HI, H_2	plenty HI, H_2, HII, dust
no SF today	active SF today
red colours	blue colours
K-star absorption line	hot star + emission line

spectrum

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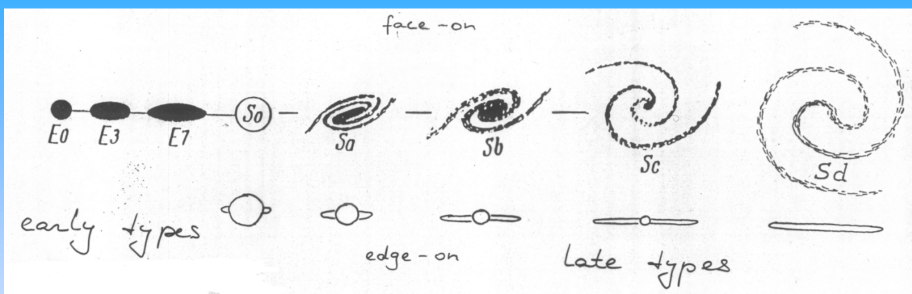
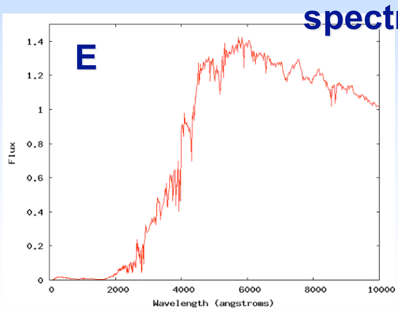
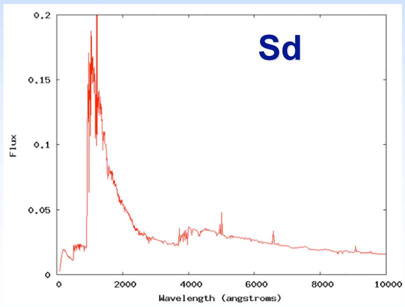
The Hubble Sequence of Normal Galaxies



early type | spectra | late type galaxies





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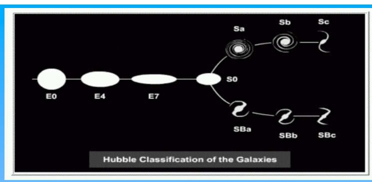
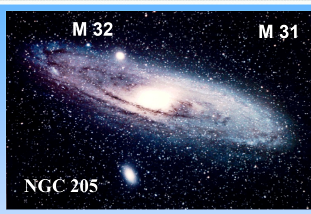
(E. Hubble 1923ff)





Cosmic Microwave Background :

Universe at z=1000 extremely homogeneous & isotropic

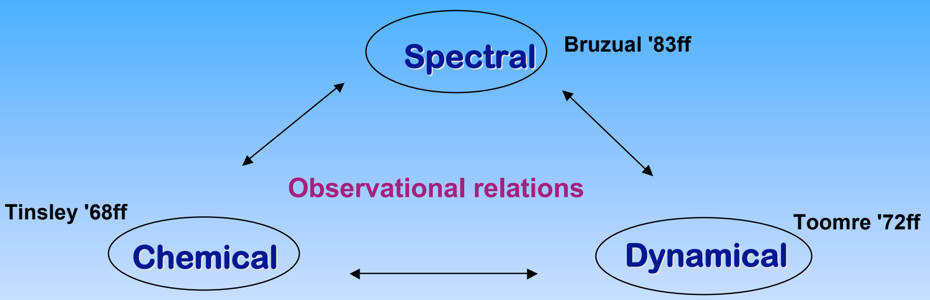
? Splendid manifold of local galaxies ?

? Relation of distant galaxies to local ones ?

Observations = snapshots

Evolution of galaxies ↔ numerical models

3 Aspects of Galaxy Evolution



Originally modelled 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

*Hertha-Sponer Research Award Dt. Physikal. Ges. 2003

Galaxy – Galaxy Interactions

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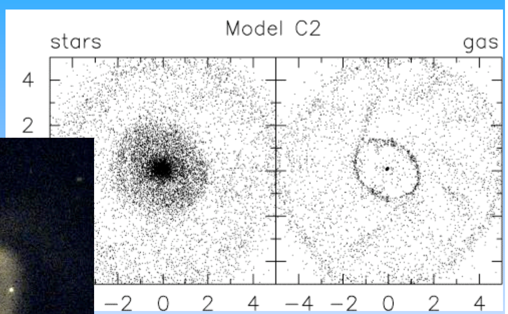
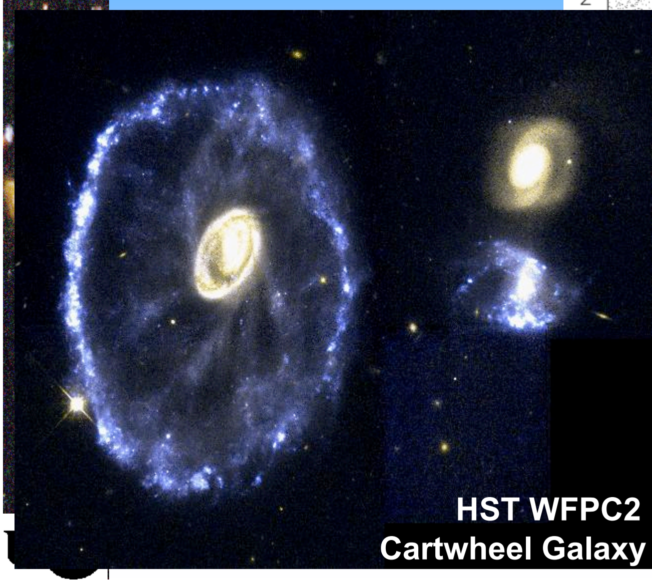
Galaxy Interactions





(Berentzen et al. 03)
GRAPE-3AF simulation

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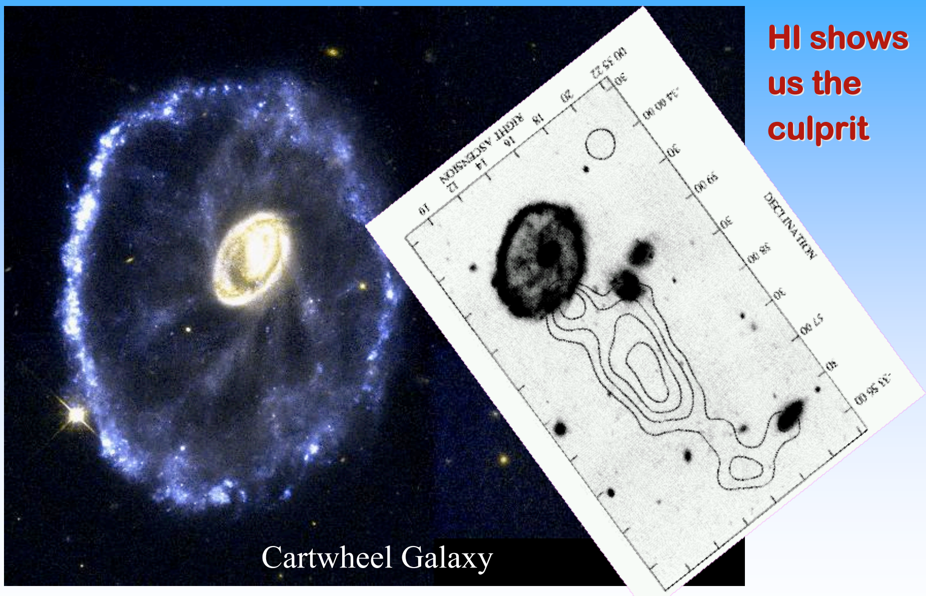
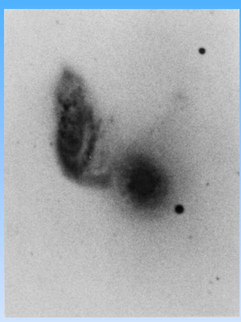
Galaxy Interactions

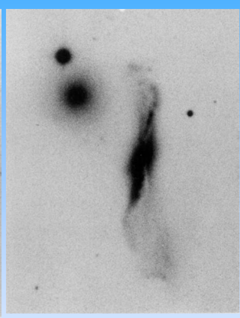


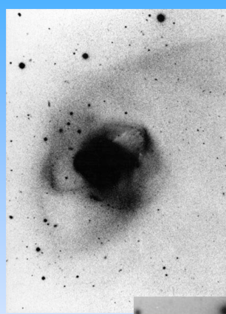
HI shows us the culprit

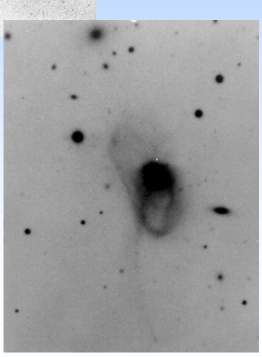
Galaxy Interactions

Arp's Atlas of Peculiar Galaxies : 1966









Arp & Madore Atlas : 1987

hundreds of disturbed galaxies

Galaxy Interactions

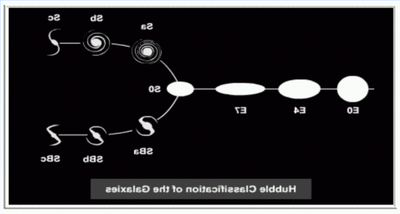
$\langle$star $\leftrightarrow$ star$\rangle \simeq 10^7 \langle \varnothing_\star \rangle$

$\langle$galaxy $\leftrightarrow$ galaxy$\rangle \simeq 40 \langle \varnothing_{gal} \rangle$

$\Rightarrow$ <1 major merger / galaxy / Hubble time>

\+ many minor ones !

Toomre & Toomre (1972): Hubble sequence not *ab initio ad infinitum*



☛ Morphological transformations

spiral + spiral → E/S0

disk + dwarf galaxy → bulge (e.g. Sd + dwarf → Sb, Sa)

Galaxy Interactions

Toomre & Toomre (1972): restricted N-body simulation ☛ Morphological transformations

spiral + spiral → E/S0

disk + dwarf galaxy → bulge (e.g. Sd + dwarf → Sb, Sa)

Parameter study: merging only at low relative velocities

Formation of bridges and tidal tails

Age sequence of 11 interacting systems from Arp's

The Toomre Sequence of Mergers

Arp 244 = NGC 4038/39
(= Antennae)
Arp 242 = NGC 4676
NGC 7592
NGC 7764
Arp 81 = NGC 6621
Arp 335 = NGC 3509
Arp 157 = NGC 520
Arp 243 = NGC 2623
NGC 3256
Arp 224 = NGC 392
Arp 226 = NGC 7252

Galaxy Interactions

⇒ <1 major merger / galaxy / Hubble time>
+ many minor ones !

Toomre & Toomre (1977): Estimate of galaxy merger rate:
11 out of 4000 NGC gals look like mergers

11/4000 × age(Universe)/τ(interaction) × 3* = 0.20

*interactions more frequent in earlier times

∑(E+S0)/∑all gals (NGC) = 800/4000 = 0.20

☛ all E/S0s could be merger remnants.

Galaxy Interactions

⇒ <1 major merger / galaxy / Hubble time>

\+ many minor ones !

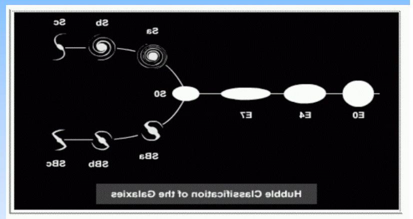
Toomre & Toomre (1972): Hubble sequence not ab initio ad infinitum

☛ Morphological transformations

spiral + spiral → E/S0

disk + dwarf galaxy → bulge

(e.g. Sd + dwarf → Sb, Sa)



Observations vs modeling :

☛ Interactions/merger involving gas-rich galaxies can trigger strong starbursts with extremely high star formation efficiencies

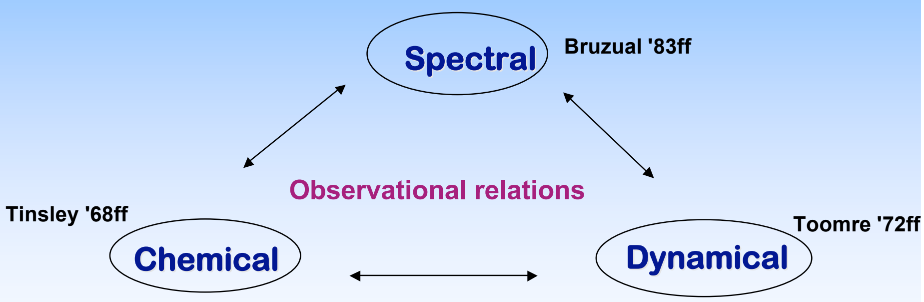
⇒ spectral transformation: spiral + spiral + starburst → E

(Fritze & Gerhard 1994a,b, Fritze & Burkert 1995)

Observations = snapshots

Evolution of galaxies ↔ numerical models

3 Aspects of Galaxy Evolution



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)

Chemical Evolution : Gas & Stars

Big Bang : H, He, (...., Li)

all heavy elements (> H, He := astrophys. „metals“)

- ☞ fusioned within stars,
- ☞ get back into gas phase by stellar winds, PN, SNe
- ☞ built into later stellar generations

Chemical abundances in the gas determined by

→ Stellar Initial Mass Function
→ Star Formation History of the galaxy
→ Stellar lifetimes & yields (mass, composition)
→ In- & outflow of gas

→ Z^{Gas} (t), X_i^{Gas} (t) from modified Tinsley (68ff) equations
+ SNIa contributions

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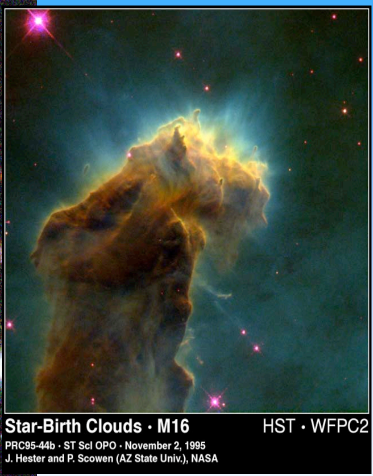
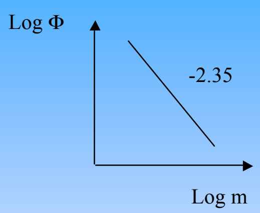
Chemical & Spectral Evolution of a Galaxy
GALEV





Normalisation :

$$\int_{ml}^{mup} m\,\Phi(m)\,dm = 1$$

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

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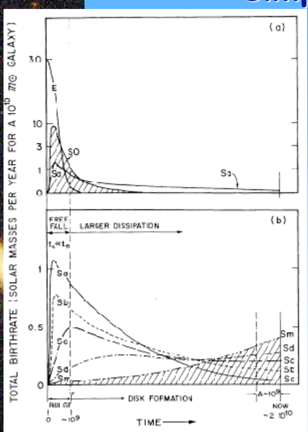
Chemical & Spectral Evolution of a Galaxy
GALEV

Simplified parameterisations : SFR(t) = Ψ(t)

SFR (E) ~ exp (-t / 1 Gyr)
SFR (Sp) ~ a · G(t) / M (t)



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)

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

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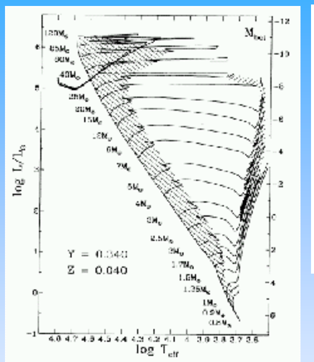
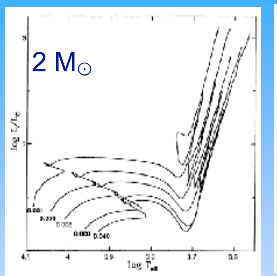
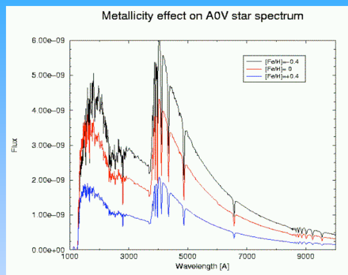
Chemical & Spectral Evolution of Galaxies







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

Z=0.004 $\tau(1\ M_\odot) \sim 7{*}10^9$ yr, $\tau(100\ M_\odot) \sim 3{*}10^6$ yr

Stellar population :

➜ Stellar Initial Mass Function

➜ Star Formation History of the galaxy

➜ Stellar evolutionary tracks, lifetimes (m, Z) & yields (m, Z)

Stellar nucleosynthesis & yields

Big bang formed H, He, traces of Li.

All other elements have beed produced by nuclear fusion in the cores of stars.

Stars lose mass (=gas) in

☆ stellar winds in late evolutionary phases

heavily dependent on stellar mass and metallicity $\dot{M}_{wind} \sim Z^4$

☆ PNe

winds & PNe : H, He, C, N, O

☆ SNe

SNe type II : O, Ne, Mg, Si, S, Ar, Ca, Ti
(= α - elements)

in/after explosion: rapid & slow neutron capture
r- & s-process elements (Ti, Cr, Fe, Ni; Sr, Ba, Pb)

SN type Ia : Ni ➝ Fe

New stars are then formed out of more enriched gas …
➜ cosmic cycle.

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Chemical Abundances

Definitions :

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

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

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

$Z_\odot \sim 0.02 \quad \leftrightarrow \quad 12+\log(O/H) = 8.9$

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 Abundances

Definitions :

stellar metallicities/abundances:

from stellar absorption lines

(e.g. Lick indices)

problems : spectral resol., S/N, crowding of lines, no clean features

(e.g. Fe line contains 40% contribution from Ca)

(Tripicco & Bell 95)

given in terms of $[X/H] := \log (X/H) - \log (X/H)_{\odot}$

mass fractions !

often : [Fe/H], but also : [Mg/H], [Mg/Fe], [α/Fe]

[Fe/H] = 0 solar

= -1 1/10 solar

= -2 1/100 solar

Chemical Evolution of Galaxies

Type Ia SNe : account for ~50% Fe in galaxies

Single-degenerate scenario (Whelan & Iben 1974):

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

primary becomes C-O white dwarf

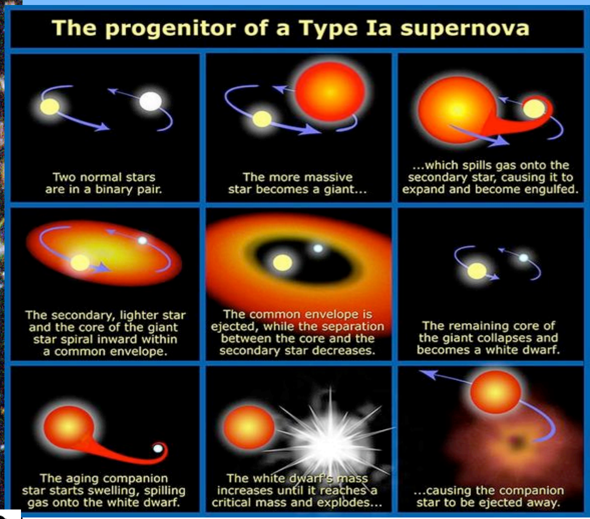
secondary becomes RG : fills its Roche lobe, mass flows onto the WD, drives it towards the Chandrasekhar limit: primary explodes by C-deflagration & produces $0.6\ M_{\odot}$ Fe

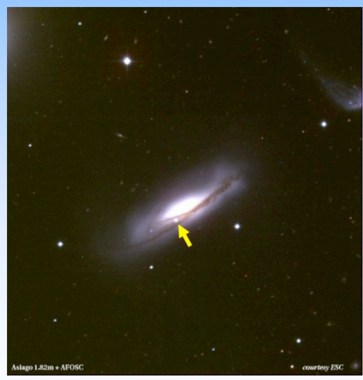
+ traces of other elements from C to Si

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

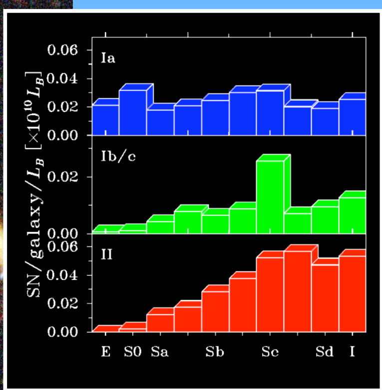
Chemical Evolution of Galaxies

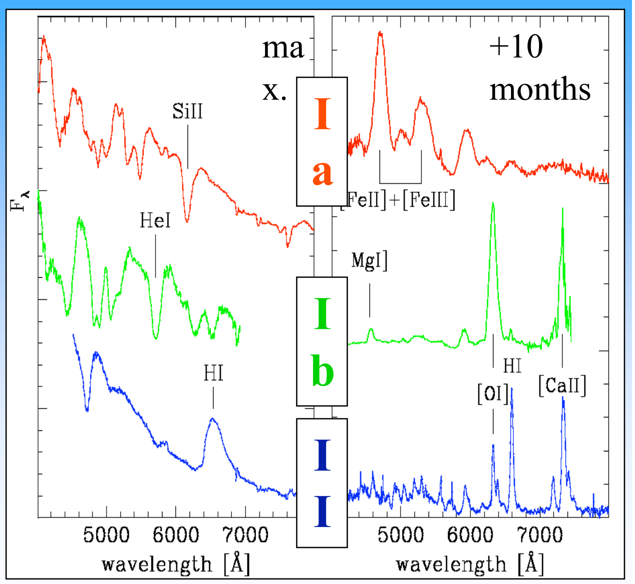
Type Ia SNe :
Single-degenerate scenario (Whelan & Iben 1974):





Basic SN types and rates





(adopted from Matteucci 07)

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 ?

Timescale for SNII enrichment ~ 10^6 yr

Chemical Evolution of Galaxies

Infall/outflow rates:

closed box : no infall/outflow

open systems : infall rate $F(t)$

const. in time or

$\sim \exp(-t/\tau)$ or even $\sim \exp(-t/\tau(r))$

outflow rate $E(t)$

$\sim SFR(t)$

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

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Modelling 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)

Modelling 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)

Modelling the Chemical Evolution of Galaxies

Equations :

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

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

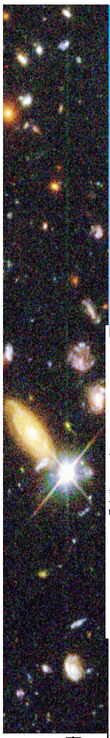
Modelling the Chemical Evolution of Galaxies

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).

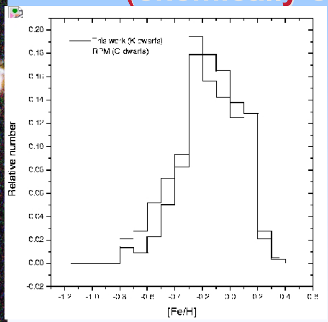


Modelling the Chemical Evolution of Galaxies

- ∗ 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)



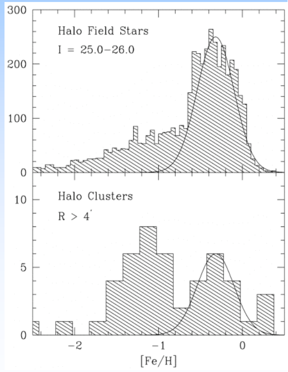
Metall. distribution of solar neighborhood stars

(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] > 2 dex

Metall. distribution of halo stars and GCs in NGC 5128

(Harris et al. 1999)



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