Chemical Evolution during Starbursts

ISM: strong increase in metallicity Z during starburst

in particular for SNII products :

[Mg/Fe] ↗, [C/O] ↘ , [N/O] ↘

reflected in stars & star clusters forming late in long bursts

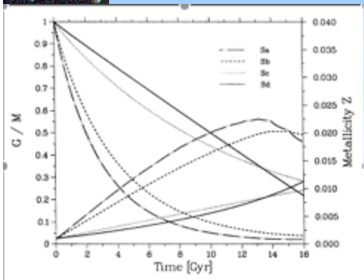


Fig. 3. Evolution of the gas fraction G/M and the global metallicity Z in different merger progenitor models

(Fritze & Gerhard1994a,b)

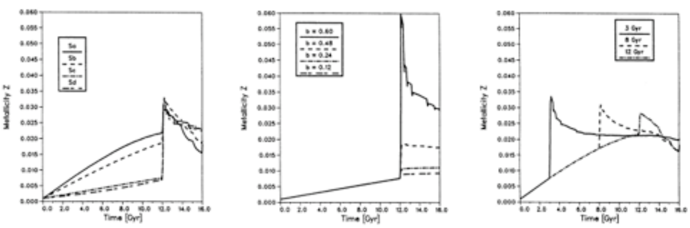


Fig. 12. Time evolution of the global ISM metallicity Z, for **a** different Hubble types, **b** different burst strengths in a 12 Gyr old $Sc - Sc$ pair, **c** maximal bursts at different bursts times in an $Sa - Sa$ pair

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
→ Star Formation History of the galaxy
→ Stellar lifetimes & evolutionary tracks (mass, composition)

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

N_{Lyc} : Schaerer & de Koter 1997, Smith et al. 2003
Line Ratios : Izotov et al. 1994, 1997, 1998

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

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

solar scaled abundances

all stellar input physics depends significantly on metallicity and so does the output !

GALEV Evolutionary Synthesis Models

Output :

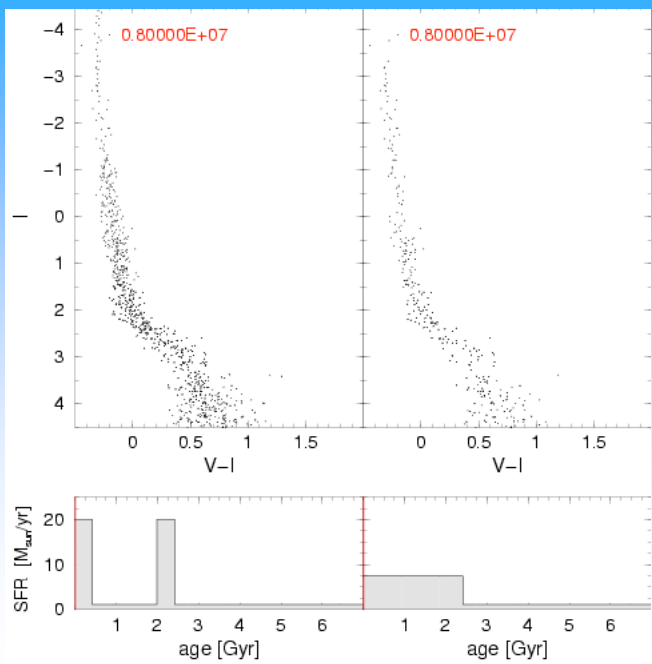
Time evolution of **CMDs** for resolved stellar populations

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)

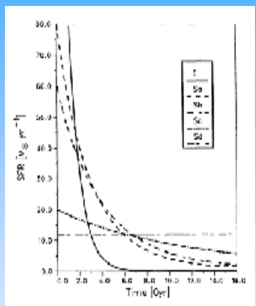


run/stop:
click on
picture

Spectral Evolution of a Galaxy

Star Formation History Ψ(t) -- single burst --> star cluster

-- extended --> galaxies



Initial Mass Function : Salpeter, Kroupa, ...

\+ Stellar evolutionary tracks / isochrones

--> HRD / CMD (t) (star cluster / galaxy)

\+ Spectra

--> integrated spectrum (t) (star cluster / galaxy)

\+ Filter characteristics/zeropoints

--> integrated luminosities, magnitudes, colors

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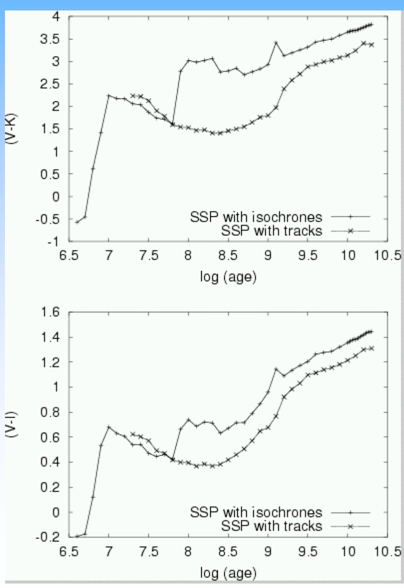
Simple Stellar Populations

Completeness 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)

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Gaseous Emission

Gaseous emission important 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

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

hydrogen line ratios : atomic physics

(Lyman, Balmer, Paschen, Brackett series)

heavy element line ratios : depend on metallicity

- from photoionisation models
- from observations

Continuous emission ~ N_{Lyc}

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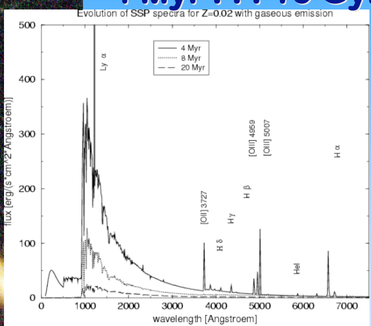
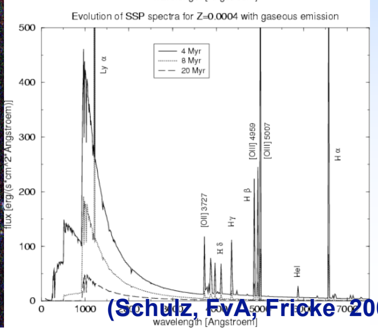
Evolution of 1 Generation of Stars

Simple **S**tellar **P**opulation (= **SSP** = star cluster)

4 Myr . . . 16 Gyr effects of the chemical composition





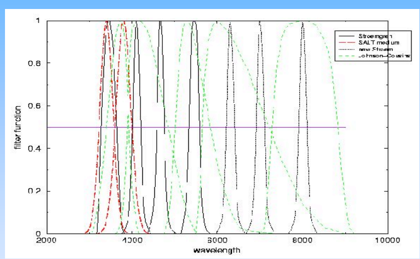
4 Myr

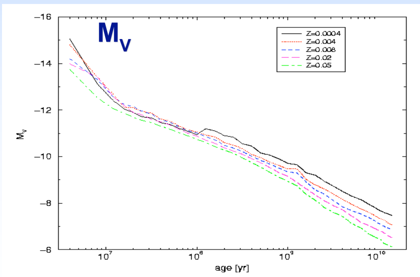
8 Myr

20 Myr

Solar metallicity

[Fe/H]= - 1.7





(Schulz, FvA, Fricke 2002, Anders & FvA 2003)

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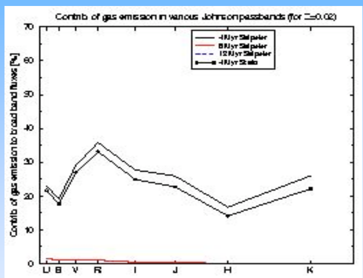
Simple Stellar Populations

Gaseous emission : at young ages 6 . . . 15 Myr

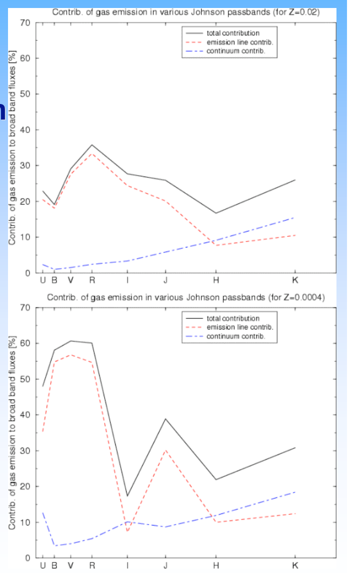
effects of metallicity

$Z_\odot$

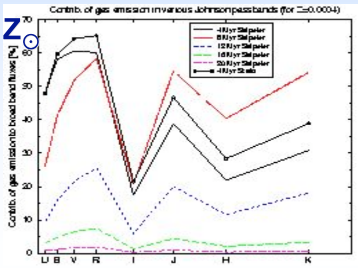


lines

continuum



1/50 $Z_\odot$



4 Myr
8 Myr
12 Myr
16 Myr
20 Myr

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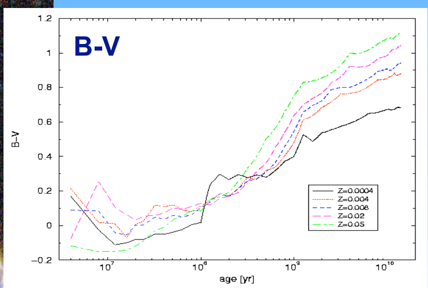
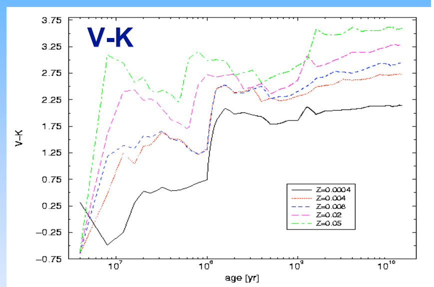
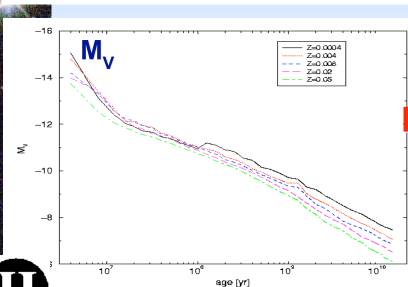
Evolution of a Simple Stellar Population

(Schulz, FvA, Fricke 2002, Anders & FvA 2003) (= star cluster)

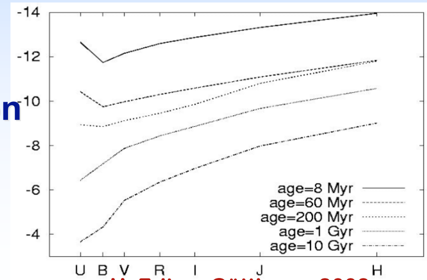
http://www.star.herts.ac.uk/~ufritze/galev/







Spectral
Energy
Distribution
SED



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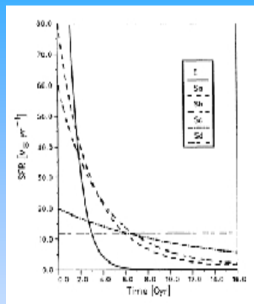
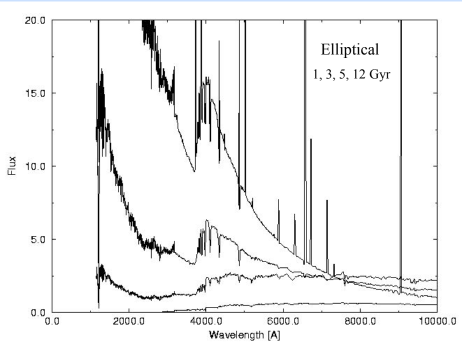
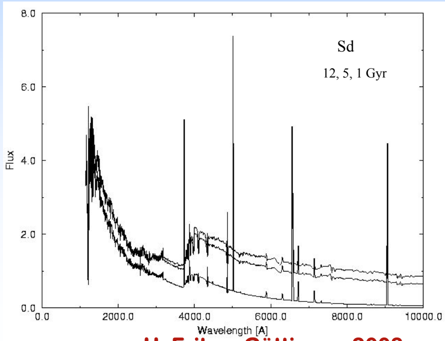
Spectral Evolution of a Galaxy

Stellar population :
➜ Stellar Initial Mass Function
➜ Stellar evolutionary tracks (m, Z)
➜ Star Formation Histories of various
galaxy types







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Chemically Consistent Evolutionary Synthesis
GALEV

simultaneous modelling of the

★ chemical evolution of the gas/ISM and the

★ spectral evolution of the stellar component (incl. gaseous emission : HII regions)

➜ chemically consistent approach

: = account for increasing initial abundances of successive stellar generations

by using input physics of appropriate metallicity for each stellar generation

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Why Chemically Consistent Modelling ?

★ Bulk of local galaxy population have subsolar abundances

late – type & dwarf galaxies

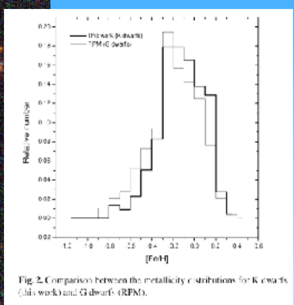
★ Normal local galaxies feature broad stellar metallicity distributions

solar neighbourhood, MW & M31 bulges, ellipticals

★ Distant galaxies are less evolved / enriched

in particular the faint ones in Deep Fields

Observed Stellar Metallicity Distributions

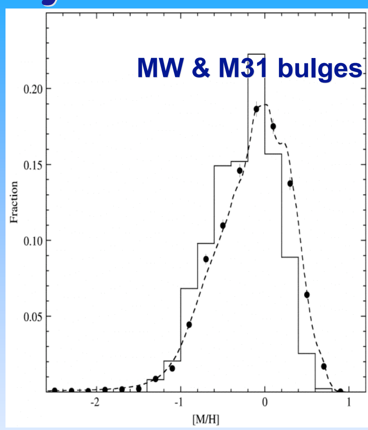


Solar neigh-bourhood
G-, K-, M- stars

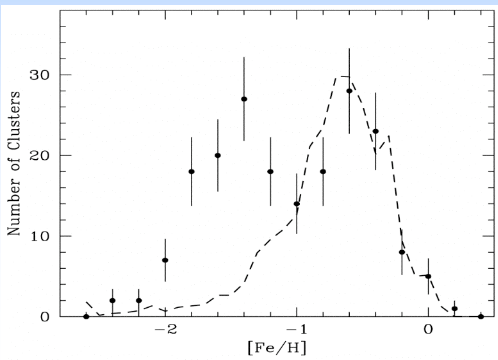
(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] ~ 2 dex

MW & M31 bulges



(Sarajedini & Jablonka 05)



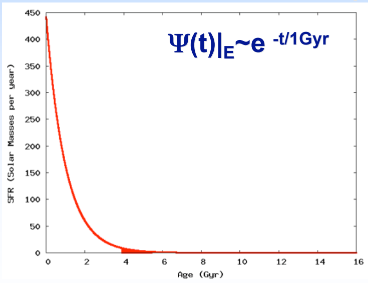
E : NGC 5128 halo

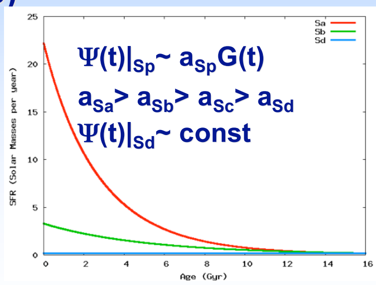
(Harris & Harris 2000)

Trends along the Hubble Sequence

- Morphology : Bulge/disk light ratio ✔
- Colours
- Spectra
- SFR_0
- Luminosities
- Composition: stars, gas, dust
- Metallicities: chemical composition

All trends can be explained by differences in the Star Formation Histories (= SFHs)





SFR = Star Formation Rate; SFH = SFR(t)

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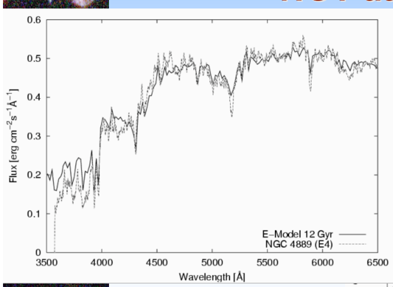
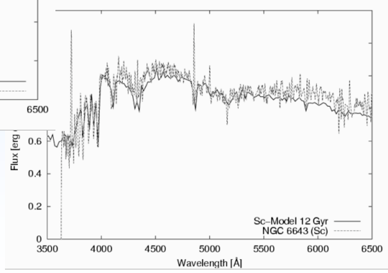
Trends along the Hubble Sequence

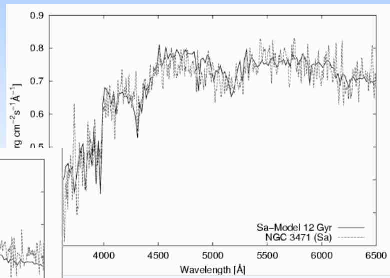
- Spectra : Kennicutt 1992, Kinney et al. 1996

Template spectra of different galaxy types

Spectral type ↔ morphological type
in the local universe ✔
NOT at high redshift !







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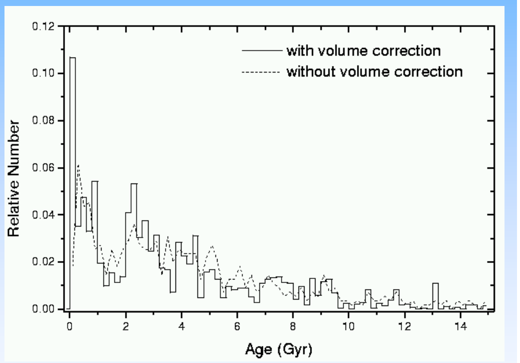
The Star Formation History of the Milky Way

Sbc galaxy

Rocha-Pinto+2000, Rocha-Pinto & Maciel 1997, 1998

from individual star age and metallicity determinations



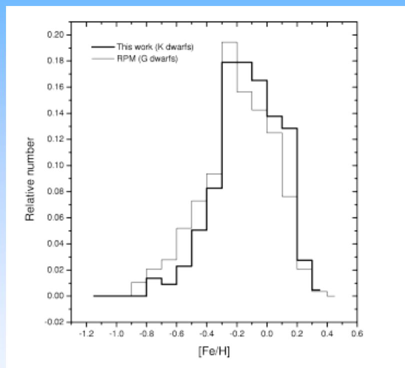


Fig. 2. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM).

Decrease by factor ~4 since the beginning +
short-term (10^8yr) fluctuations by factor < 2 around simple model SFH

Broad (>factor 10) stellar metallicity distribution
⟨[Fe/H]⟩ < 0 subsolar

Implications for Local Galaxies

SFRs from H_α , O[II], UV severely overestimated for low metallicity galaxies

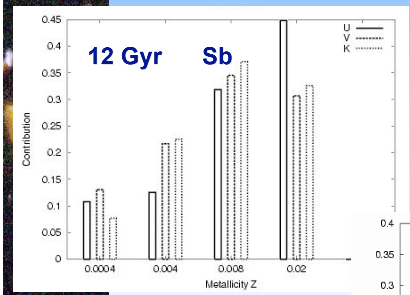
	Z=0.0004 I ZW 18, SBS 0335	$Z_\odot$	Z=0.05
H_α	2	1	0.85
O[II]	3	1	0.87
UV(1500)	1.3	1	0.89
UV(2800)	1.4	1	0.89

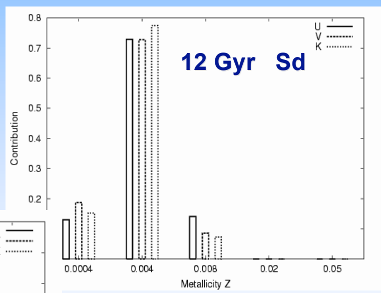
when using standard calibrations (Kennicutt 98, Gallagher et al. 89) valid for $Z \sim Z_\odot$
(Bicker & FvA 2005)

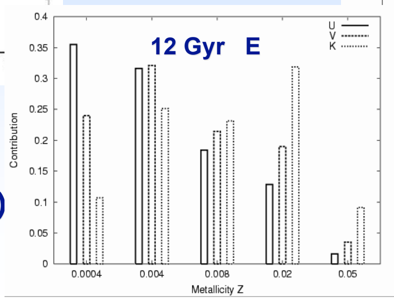
Chemically Consistent Evolutionary Synthesis

Stellar metallicity distributions in model galaxies

➜ light contributions from different metallicity & age subpopulations dominate at different wavelengths







(Bicker et al. 2004)

Elliptical ≠ SSP

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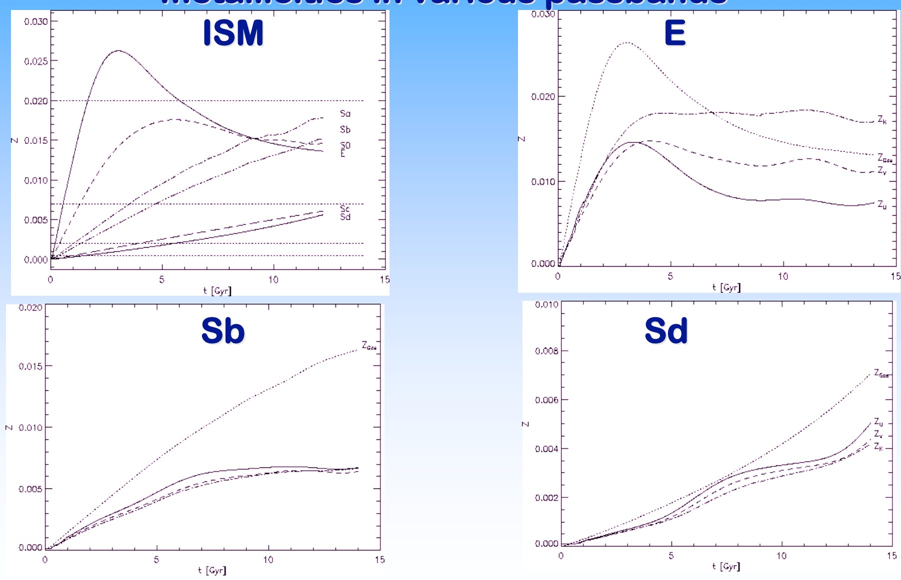
Chemically Consistent Evolutionary Synthesis

ISM abundances and luminosity weighted stellar metallicities in various passbands



Möller, FvA, Fricke 1997

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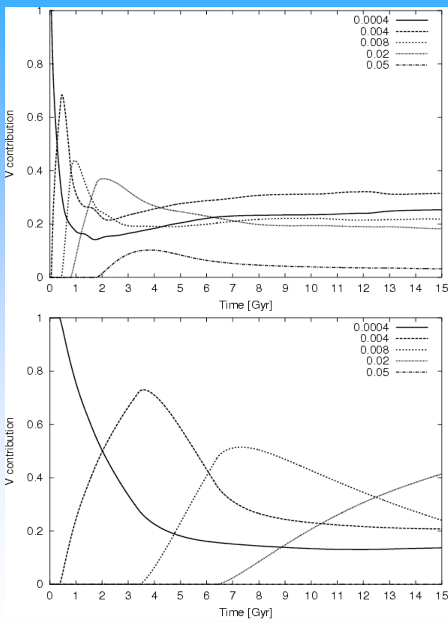
Chemically Consistent Evolutionary Synthesis



V – band luminosity contributions of different metallicity subpopulations

E

Sb

Bicker, FvA, Möller 2004

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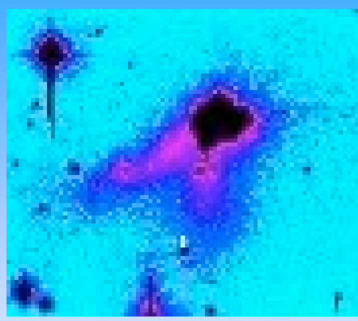
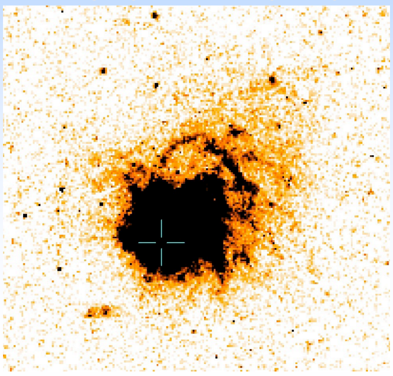
Blue Compact Dwarf Galaxies

BCDGs: blue, compact,
often irregular, unrelaxed,
gas-rich, SFR_o » $<SFR>_{past}$,
HI consumption timescale « t_{Hubble},
very metal-poor $<Z> \sim 1/10\ Z_{\odot}$,
1 - several starburst knots on top
of older stellar population (NIR)





Papaderos et al.

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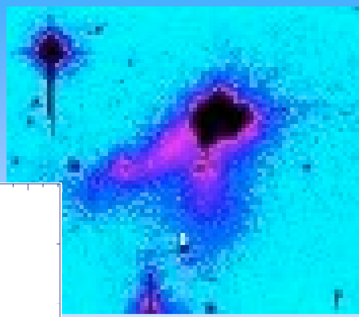
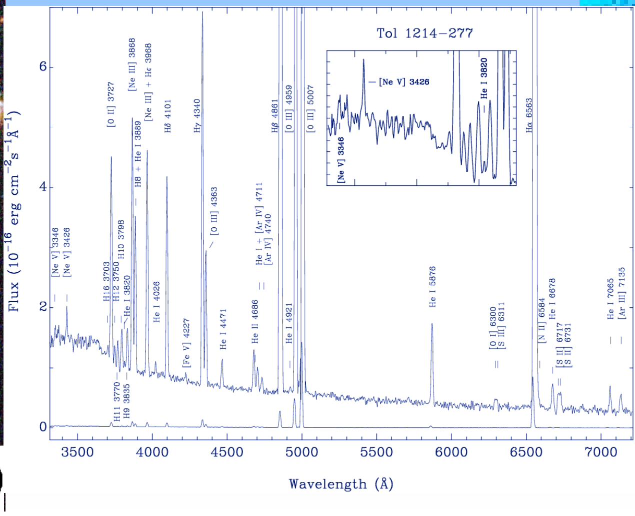
Blue Compact Dwarf Galaxies





Papaderos et al.

Blue Compact Dwarf Galaxies

Models for underlying galaxy (ug) E, Sd + ongoing starburst

Starburst parameters:
- time of onset (=age of ug)
- increase of SFR
- duration of the burst (10^5 – 10^6 yr in dwarf galaxies ~ dynamical timescale)
- age of the starburst

Burst strength : b := ΔS/S or (b :=) ΔS/G =: SFE

Type & age of ug determined from outer regions/NIR colours

Burst properties from colours (1st estimates)
& spectra (more accurate determinations)

Blue Compact Dwarf Galaxies

ug

Ψ_1 : const. SFR

Ψ_2 : exp. declining SFR

different burst strengths

(Krüger et al. 1991)

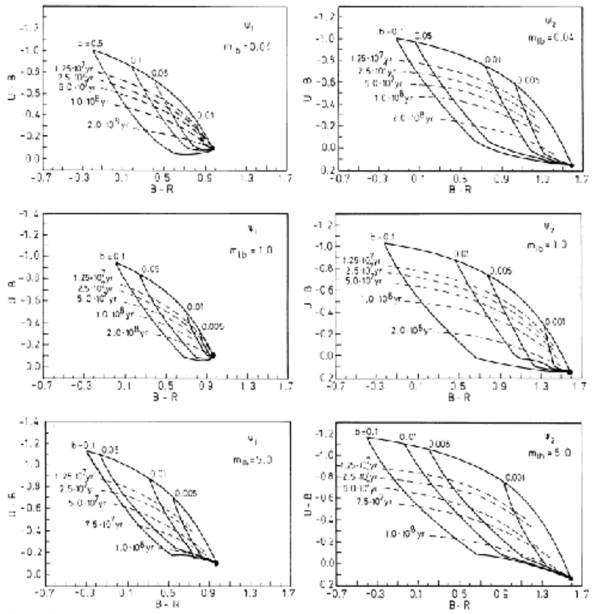


Fig. 4a–c. Theoretical two-colour plots for star bursts at time $T = 15$ Gyr and duration $t_b = 5 \cdot 10^6$ yr in an underlying galaxy having constant SFR Ψ_1 for various lower mass limits of the burst-IMF. The numbers indicated on the curves are the burst strengths b and the times since star formation in the burst has ceased (isochrones) respectively. The symbol ● denotes the underlying galaxy

Fig. 5a–c. Same as Fig. 4, but for the exponentially decreasing SFR Ψ_2 in the underlying galaxy without gas infall

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Blue Compact Dwarf Galaxies

Huge impact of gaseous emission on broad band colours during active burst phase

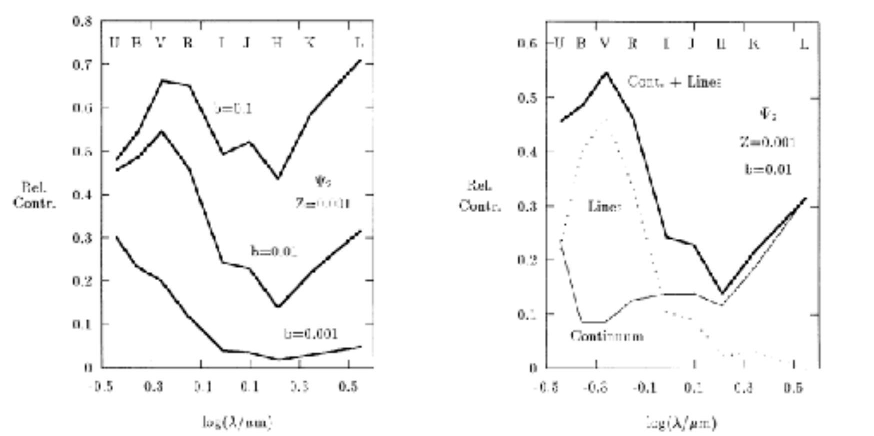

Fig. 3. Relative contribution of the interstellar gas to the total emission of the model galaxies in the UBVRIJHKL bandpasses. The contribution at the end of a starburst lasting $5 \cdot 10^5$ yr is shown. Left: relative contribution of the total gaseous component to the flux of the galaxy for various burst strengths. Right: contribution of the emission lines and the gaseous continuum to the total flux of the galaxy for $b = 0.01$

(Krüger et al. 1995)

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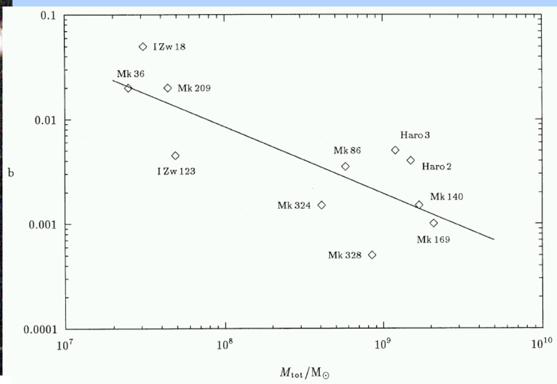
Blue Compact Dwarf Galaxies

GALEV evol. synth. for sample of BCDs
with photometry in BVI+JHK :

SFR ~ 0.1 - 10 $M_\odot$/yr

burst strength $b := \Delta S_{burst} / S$ → post - starbursts
b=0.001 - 0.05,



mini bursts as compared
to mergers !

b ↘ for M_{tot} ↗

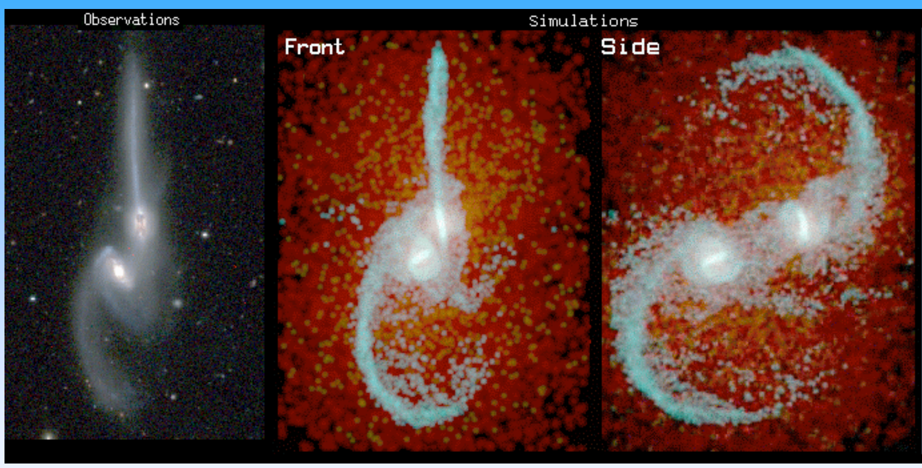
okay with stochastic
self-propagating SF

(Krüger, FvA, Loose 1995)

Galaxy – Galaxy Interactions

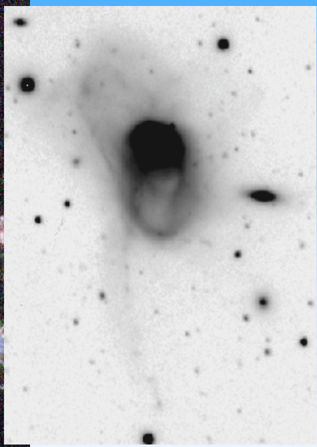
The Toomre Sequence of Mergers

The Toomre Sequence of Mergers



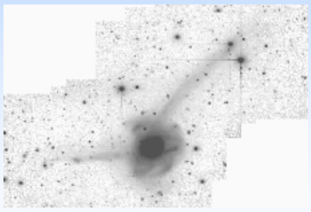
Barnes & Hibbard 02

The Toomre Sequence of Mergers



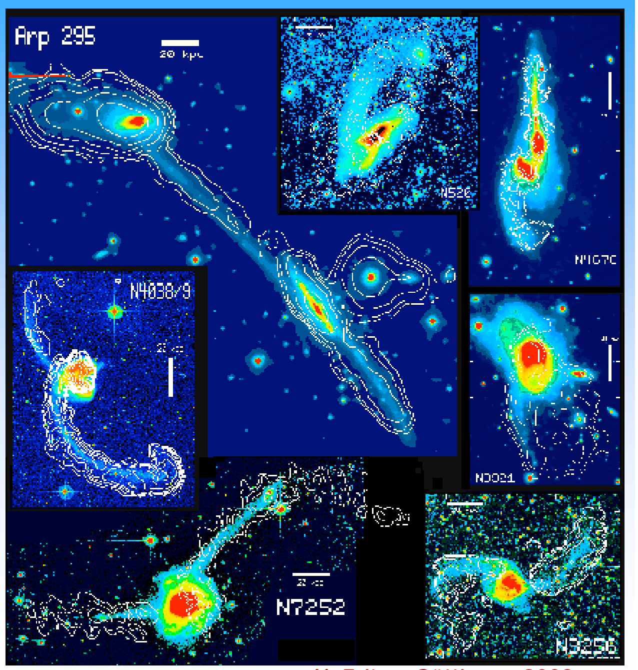
NGC3921

NGC 7252



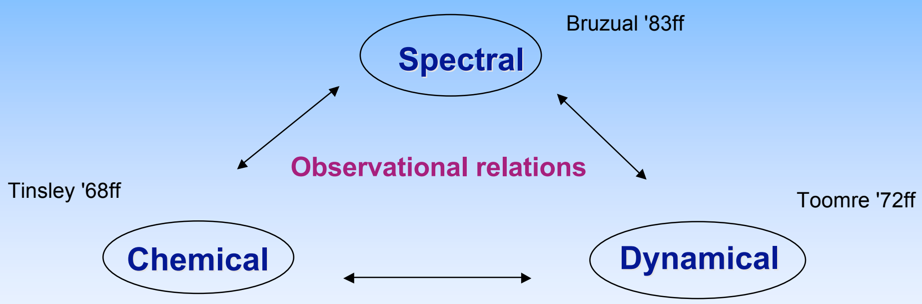
The Toomre Sequence of Mergers

HI observations
(Hibbard+02)



Dynamical Evolution of a Galaxies

= 3rd aspect of galaxy evolution



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

Dynamical Evolution / Formation of Galaxies

Gravitation & Hydrodynamics :

Dark matter	: semianalyt. / numer. N-body	-	dissipationsless
Stars :	N-Body-Tree-Codes	-	collisionless
Gas :	(Smooth Particle) Hydrodynamics (+ Tree-Codes)	-	dissipative

+ Star Formation Criterium + Feedback

↓

(radiation, mechan. energy, mass, heavy elements) from stars and AGB

➜ galaxy interactions

➜ galaxy formation

Galaxy Interactions

Toomre & Toomre 1972 ff : first numerical modelling of disk – disk interactions : N-body (N=128 ...)

- ☛ tidal tails & bridges
- ☛ morphological transformation of disks ➜ spheroids

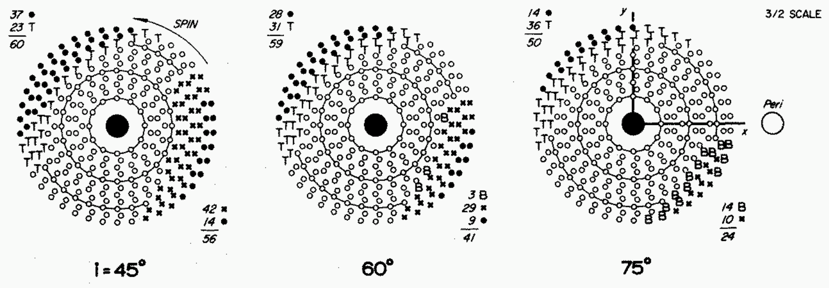


FIG. 15.—Scorecards of tail-making and accretion for three ($i = 45°$, $60°$, and $75°$) inclined $\omega = 0°$ parabolic passages of a companion of equal mass. The open symbols represent test particles retained by the primary mass point, crosses are those captured by the intruder, T's are nonescaping tail particles which at $t = 5$ lie farther than $1.0R_{min}$ from their parent mass, B's are similar bridge-like particles, and the filled symbols denote particles that escape from both systems. The initial radii of the three connected rings were 0.2, 0.4, and $0.6R_{min}$.

Galaxy Interactions

Toomr… & Toomre 1972 ff : first numerical modelling of
di…

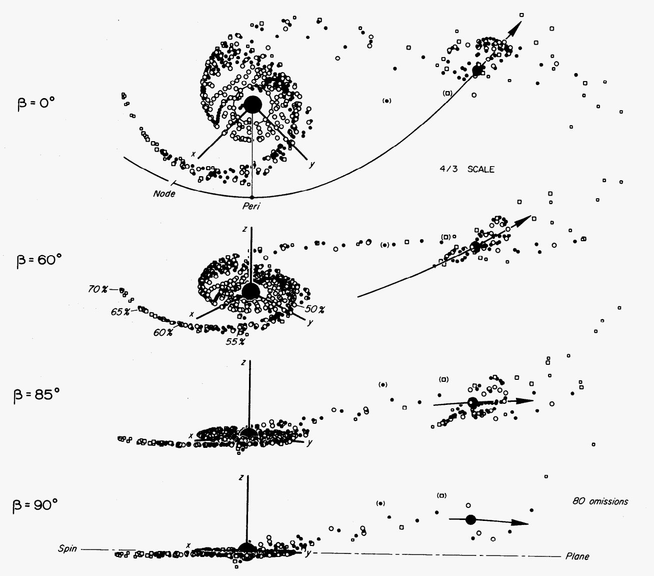


FIG. 19.—Model of Arp 295. This construction supposes a parabolic $i = 15°$, $\omega = 45°$ passage of a quarter-mass companion. Its consequences are here viewed at time $t = 4$ from longitude $\lambda = 135°$ and four distinct latitudes. Except for the heavy "spray" near the companion, the $\beta = 85°$ picture resembles our actual view of this galaxy pair; much of that clutter has been suppressed in the $\beta = 90°$ view by omitting all particles which ever passed within $0.2R_{min}$ of the companion.

Galaxy Interactions

Toomre & T

disk – c

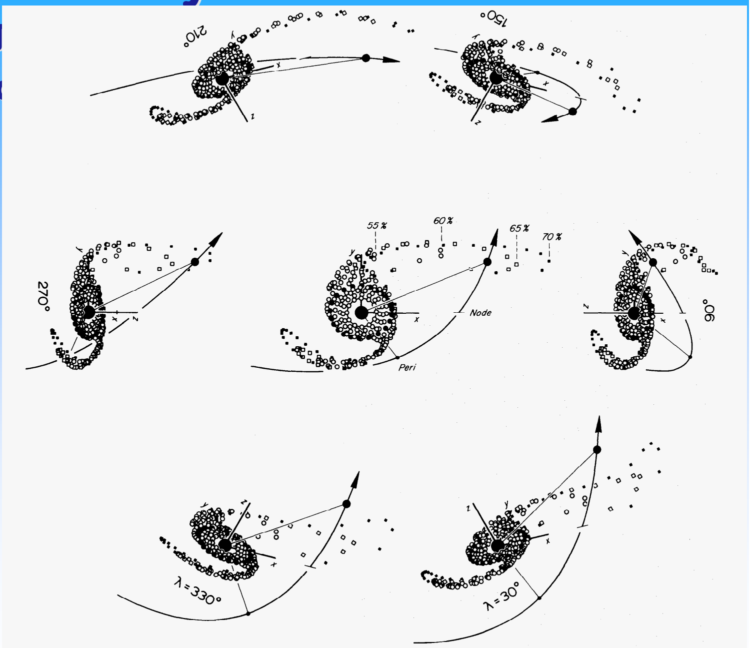
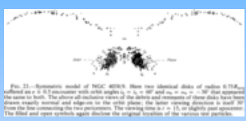


FIG. 12.—Geometric study of the $i = 45°$, $\omega = -60°$ object. Here six $\beta = 60°$ views of this object from equally spaced longitudes λ encircle its face-on view at $t = 3.143$.

Galaxy Interactions

Toomre & Toomre 1972 ff : first numerical modelling for the Antennae & other galaxies



- ★ slow prograde encounters : strongest tidal forces, nicest tails
- ★ tidal forces symetric, 1 tail per disk
- ★ tidal tails develop on t_{dyn} : $l = v_{rot} \cdot t$ after 1st pericentre
- ★ tail length ~ M_{disk} : equal length tails ~ equal mass disks
- ★ shells : minor accretion
- ★ polar ring galaxies : dwarf accretion
- ★ ring galaxies : bullet perpendicular through centre of disk

Galaxy Interactions

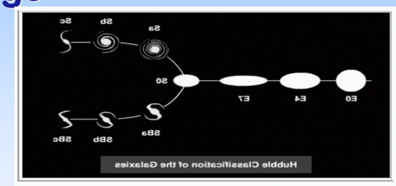
Toomre & Toomre 1972 ff : first numerical modelling for the Antennae & other galaxies

★ violent relaxation : exp. disk ➜ de Vaucouleurs profile E
➜ L-σ relation & fundamental plain relations
★ incomplete : gradients partly survive
★ propagates outward: fall-back of material, few % escape

Galaxy Interactions

Toomre & Toomre 1972 ff : first numerical modelling of disk – disk interactions : N-body (N=128 ...)
morphological transformation of disks ➜ spheroids

spiral + spiral ➜ "E"
spiral + dwarf ➜ spiral with bulge



Counterarguments :
* central densities too small
* GC specific frequencies too small

$T_{GC} := N_{GC} / M_{gal}$

$\langle T_{GC}(E) \rangle \sim 2 \langle T_{GC}(Sp) \rangle$ (Ashman & Zepf 95)

Dynamical Models & Galaxy Interactions 2008

N-body TREE Codes : stars + DM   N~10^5 -10^6

disk + bulge + halo

SPH TREE Codes : gas   (or Sticky Particles method)

➜ high gas concentrations towards centres

➜ central gas densities ~ stellar central densities of Es ✔

as observed in ULIRGs (= Ultraluminous IR Gals

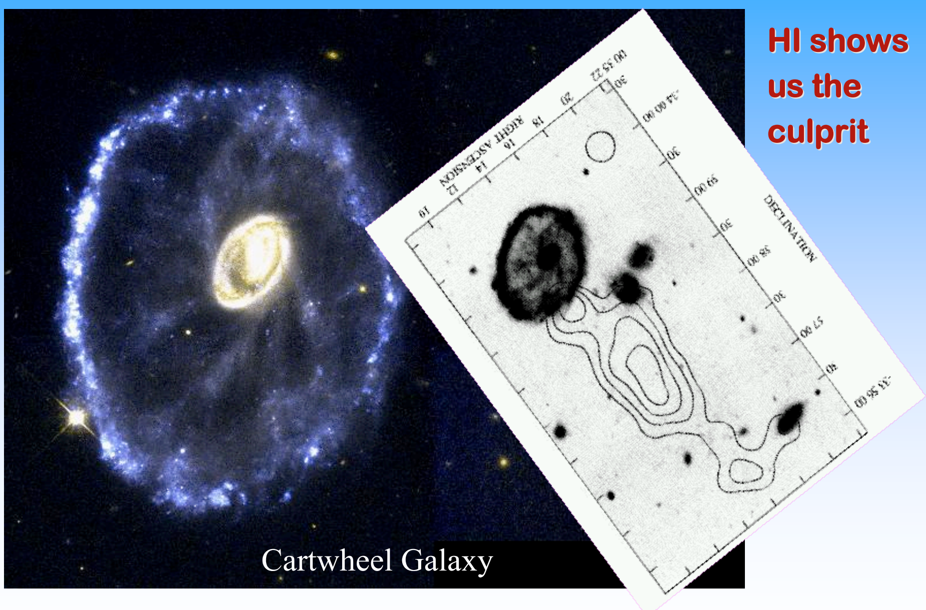
= advanced stages of gas-rich mergers)

HI from beyond the optical radius brought into the galaxy/centre

Problems : shock resolution, molecular cloud structure, multi-phase ISM, SF criterium/criteria, feedback

➜ formation of GCs in mergers : GC specific frequency ✔

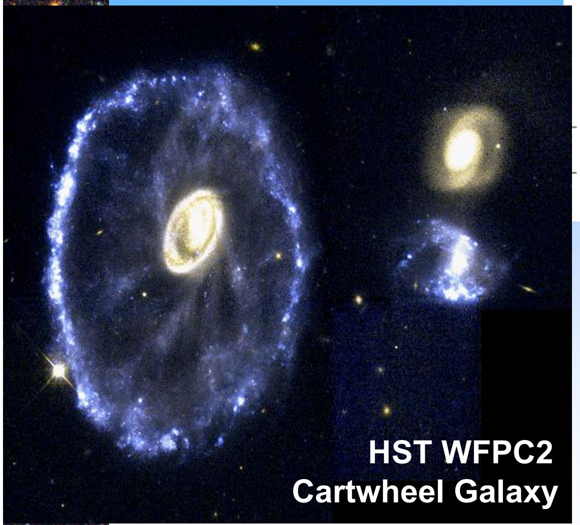
Galaxy Interactions

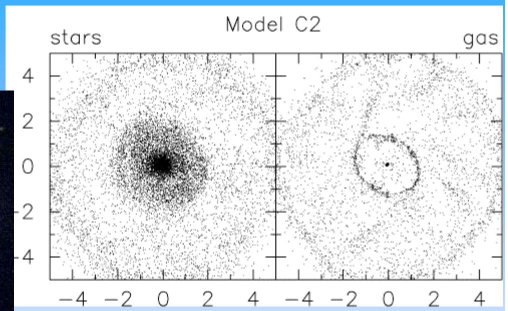


Cartwheel Galaxy

HI shows us the culprit

Galaxy Interactions





(Berentzen et al. 03)
GRAPE-3AF simulation :
stars: N-body, gas: SPH
gas traces much sharper structures than stars
with SF: young stars trace sharper structures than old ones

Dynamical Models : Galaxy Interactions

Orbital parameters & galaxy properties :

global — nuclear starbursts — AGN fuelling
(e.g. Barnes & Hernquist 1992, Jogee 2005)

prograde encounters : global starbursts (? contracting ?)
retrograde -- " -- : nuclear starbursts & AGN fuelling

Consistent inclusion of
- SF,
- AGN formation/feeding and
- feed back from both
still under construction