The Physics of Galaxies

Observations versus Theory

From the Early Universe to the Present

Part 3

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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 mergers & galaxy transformation ?

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

Comparing/gauging methods

How far back and to what accuracy can we trace galaxy SFHs ?

CMDs – integrated photometry – integr. spectra – broad band colors – Lick indices

- theoretical study accounting for typ. obs. uncertainties
  Δmag=0.05 – 0.1, Δindex=0.1Å, S/N=5 – 10
  simplified SFHs, fixed metallicity
  (Lilly & Fritze 05a, b)
- observational study : LMC bar project
  (collab. C. Gallart, D. Alloin, S. Yi, P. Demarque, ...)
  - HST resolved stellar population : Coimbra experiment
  - VLT slit trailed across same field (Alloin+02)

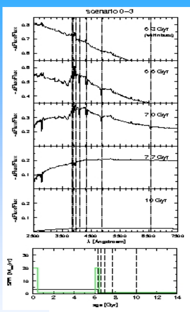
Lessons from Nearby Galaxy Studies

- no way to reveal SFH prior to a burst or prior to the last major epoch of SF
- SFR details within last ~1 Gyr best recovered from CMDs, to slightly lesser detail from integrated light
- SFR between 1 . . . 3–5 Gyr ago : roughly* recovered to similar accuracy from CMDs & integrated light
- SFR > 3–5 Gyr ago : vaguely* recovered from to similar accuracy from CMDs & integrated light

*SFR(<1 Gyr) / SFR(1 . . . 3–5 Gyr) / SFR(>3–5 Gyr)

(Lilly & Fritze 05a, b; Fritze 07, see also Cardiel et al. 03)

Long wavelength basis UV/U . . . K of multi-λ photometry compensates for lack of spectral resolution



HIRES spectroscopy / narrow band indices will do somewhat better

MgII 2798 visible for ~ 2 Gyr (early F stars)

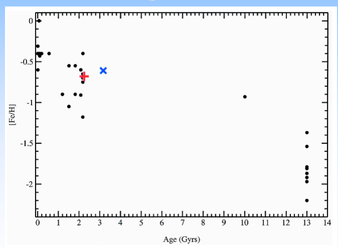
CaIIK 3933 visible for 2 – 6 Gyr (late F / early G stars)

(Lilly & Fritze 2005a, b)

Exploring the SFH of the LMC

Exploring the SFH of the LMC

Star clusters in the LMC show age gap : 10 - 3 Gyr ago
-- not seen in field stars: continuous age distribution
-- chemical enrichment continued
➜ Formation of long-lived star clusters only during peak SF phases



-- related to close passages of SMC and Milky Way ! ?

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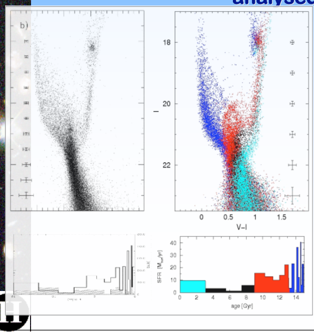
Exploring the SFH of the LMC

Deep HST imaging in V, I ➜ CMD with ~10^5 stars
(Smecker – Hane +02) down to V < 23.5 mag, analysed to obtain SFH



LMC bar field

Left : CMD & SFH from (S-H+02)
Right : GALEV model CMD using S-H's SFH

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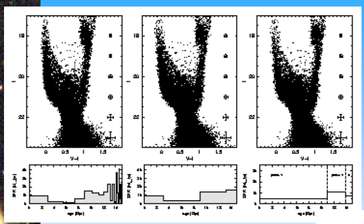
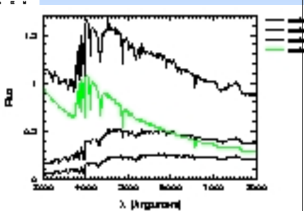
GALEV model study of accuracies in SFH determination



- toy SFH : 3 phases
  first 9 Gyr
  next 3 Gyr
  last 1 Gyr
- detailed SFH(CMD)
  → similar quality of fit



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*SFR(<1 Gyr) / SFR(1 . . . 3–5 Gyr) / SFR(>3–5 Gyr)

(Lilly & Fritze 05a, b; Fritze 07, see also Cardiel et al. 03)

Long wavelength basis UV/U . . . K of multi-λ photometry (more than) compensates for the lack of spectral resolution in derivation of SFHs over cosmological lookback times

To recover (violent) SFHs back to onset of SF : analyse age and metallicity distributions of Globular Cluster Systems

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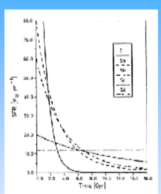
Spectral Evolution of a Galaxy

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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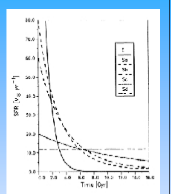
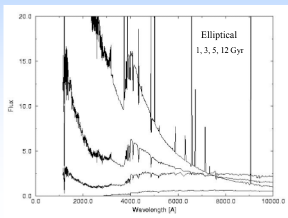
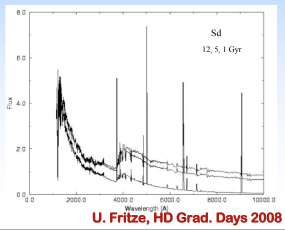
Spectral Evolution of a Galaxy

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







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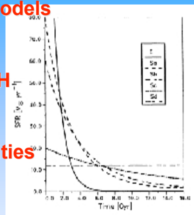
Philosophy of GALEV Models for Galaxies

Ockham's Razor: Simplest possible models

closed-box (→ inflow , outflow)

Small # of free parameters : (IMF), SFH



Calculate :

large number of observational quantities

CMDs, spectra, luminosities, colors,

emission & absorption lines, chem. gas abundances

Comparison with

- ☆ multi-band observation
- ☆ spectral & chemical properties

➜ severe constraints on free parameters

Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ average colours U – B, B – V, V – I, V – K of the respective types from RC3, Virgo, Coma samples, . . .

☆ average absorption/emission line strengths

☆ stellar metallicities (E, S0), gas metallicities (spirals)

☆ template spectra

☆ gas-to-total mass ratios

☆ average luminosities in B

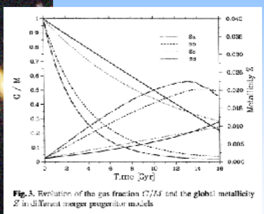
➜ tight constraints on SFHs of different spectral galaxy types

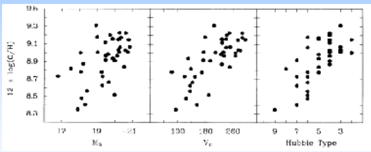
Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ average absorption/emission line strengths

☆ stellar metallicities (E, S0), gas metallicities (spirals)





(FvA & Gerhard 1994a) (Zaritsky et al. 1994)

Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ emission line strengths : SFR_o

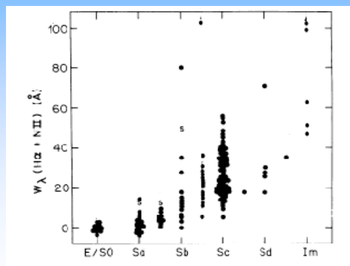


FIG. 5. Distribution of Hα + [N II] emission equivalent width, binned by RSA Hubble type. The symbol S denotes a Seyfert galaxy.

(Kennicutt & Kent 1983)

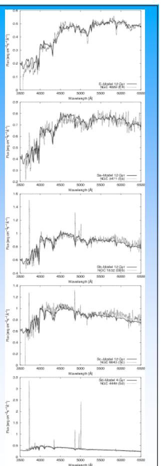
Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ template spectra

(Kennicutt 1992, Kinney et al. (UV))

(Sd template can only be fit at age ~4 Gyr)

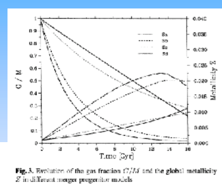


(Bicker et al. 2004)

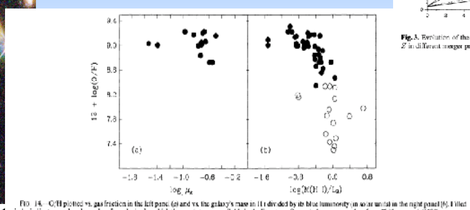
Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ gas-to-total mass ratios

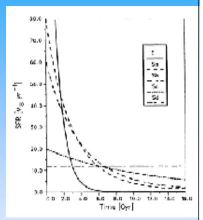


(Zaritsky et al. 1994)



GALEV Models for Galaxies E,…, Sd

With simplified parametrisations for SFH, models well describe all observed chemical and spectral properties of normal undisturbed galaxies E, S0, Sa, Sb, Sc, Sd.



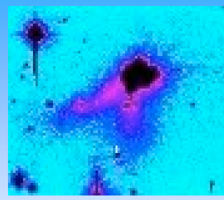
➜ try starbursts on top of undisturbed galaxies

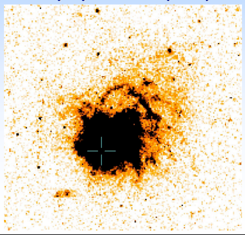
➜ analyse Blue Compact Dwarf Galaxies BCDGs

➜ analyse starbursts in interacting/merging galaxies

Blue Compact Dwarf Galaxies

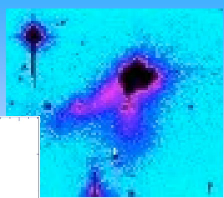
BCDGs: blue, compact,
often irregular, unrelaxed,
gas-rich, $SFR_o \gg \langle SFR\rangle_{past}$,
HI consumption timescale « t_{Hubble},
very metal-poor $\langle Z\rangle \sim 1/10\ Z_\odot$,
1 - several starburst knots on top of older stellar population (NIR)

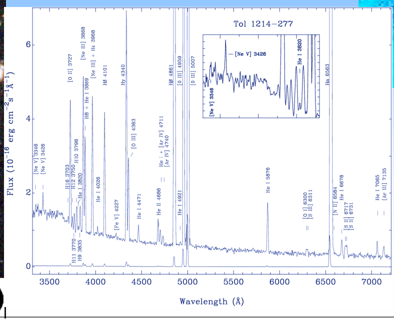




Papaderos et al.

Blue Compact Dwarf Galaxies





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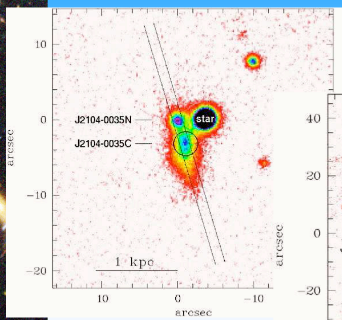

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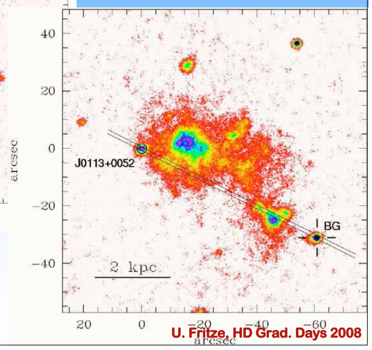


Blue Compact Dwarf Galaxies

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

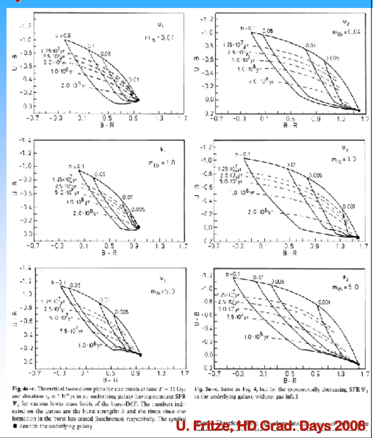
Burst properties from colours (1st estimates) & spectra (more accurate determinations)

Blue Compact Dwarf Galaxies

ug
Ψ_1 : const. SFR
Ψ_2 : exp. declining SFR

different burst strengths

(Krüger et al. 1991)



Blue Compact Dwarf Galaxies

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

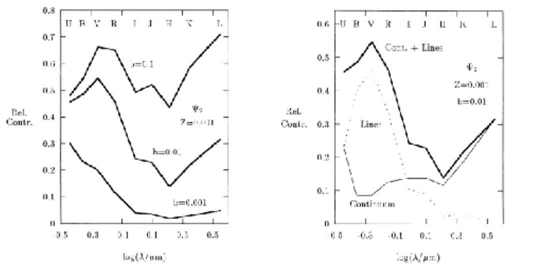


Fig. 3. Relative contribution of the interstellar gas to the total emission of the model galaxies in the UBVRIJHKL bandpasses. The contribution at the end of a starburst lasting $5 \cdot 10^5$ yr is shown. Left: relative contribution of the total gaseous component to the flux of the galaxy for various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

Blue Compact Dwarf Galaxies

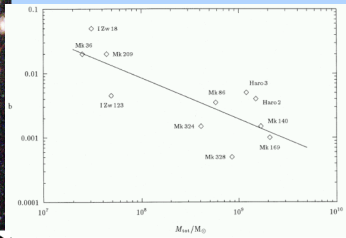
GALEV evol. synth. for sample of BCDs with photometry in BVI+JHK :

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

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

mini bursts

b ↘ for M_{tot} ↗

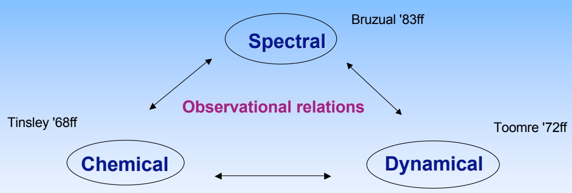


okay with stochastic self-propagating SF

(Krüger, FvA, Loose 1995)

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 - dissipative (+ Tree-Codes)

+ Star Formation Criterium + Feedback
↓
(radiation, mechan. energy, mass, heavy elements) from stars and AGB

➜ galaxy interactions

➜ galaxy formation

Galaxy – Galaxy Interactions

Galaxy Interactions

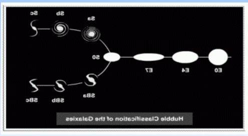
<star ↔ star> ≃ 10^7 <⌀$_\star$>

<galaxy ↔ galaxy> ≃ 40 <⌀$_{gal}$>

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

☛ Morphological transformation

spiral + spiral + starburst → E/S0
Sd + dwarf galaxy → Sb, Sa



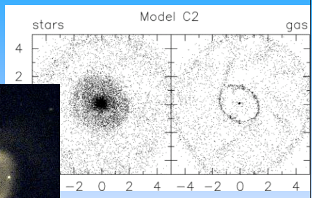
GALEV :

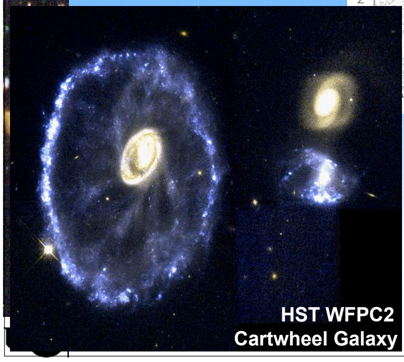
☛ Starbursts with extremely high star formation efficiencies η during interactions between gas-rich galaxies

⇒ spectral transformation spiral + spiral + starburst → E

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

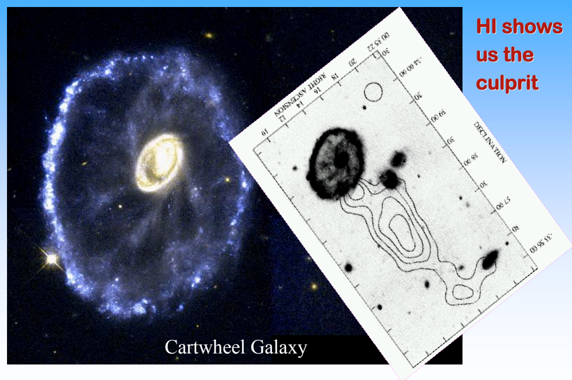
Galaxy Interactions





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

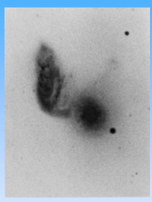
Galaxy Interactions

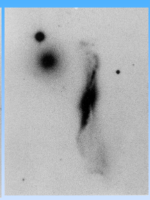


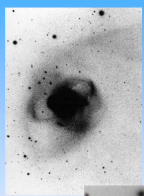
HI shows us the culprit

Galaxy Interactions

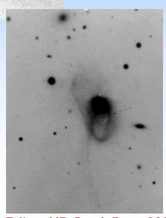
Arp's Atlas of Peculiar Galaxies : 1966







Arp & Madore Atlas : 1987



hundreds of disturbed galaxies

Galaxy Interactions

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

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

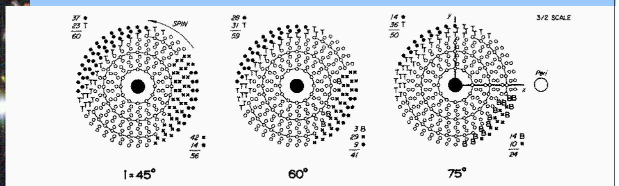


FIG. 15.—Scorecards of tail-making and accretion for three (i = 45°, 60°, and 75°) inclined ω = 0° parabolic passages of a companion of equal mass. The open symbols represent test particles retained by the primary mass point, crosses are those captured by the intruder, T's are nonescaping tail particles 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

Toomre & Toomre 1972 ff : first numerical modelling of

di

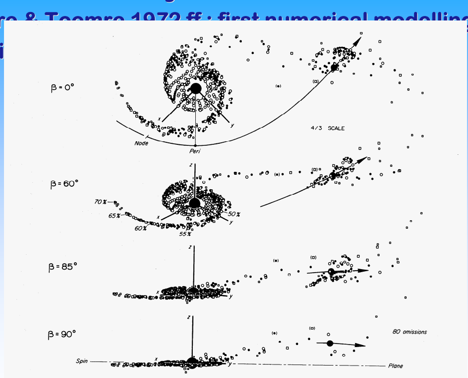


FIG. 19.—Model of Arp 295. This construction supposes a parabolic i = 15°, ω = 45° passage of a quarter-mass companion. Its consequences are here viewed at time t = 4 from longitude λ = 135° and four distinct latitudes. Except for the heavy "spray" near the companion, the β = 85° picture resembles our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

Galaxy Interactions

Toomre & T

disk – d

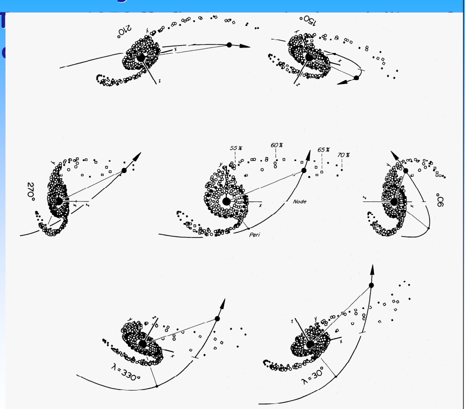
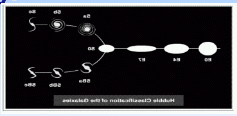


FIG. 12.—Geometric study of the i = 45°, ω = −60° object. Here six β = 60° views of this object from equally spaced longitudes λ encircle its face-

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

$T_{GC} := N_{GC} / M_{gal}$
$<T_{GC}(E)> \sim 2 <T_{GC}(Sp)>$ (Ashman & Zepf 95)

Dynamical Models : Galaxy Interactions

Dynamical models 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 ✔

Dynamical Models : Galaxy Interactions

Orbital parameters & galaxy properties :

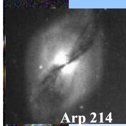
global — nuclear starbursts — AGN fuelling
(e.g. Barnes & Hernquist 1992, Jogee 2005)

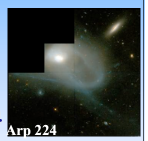
prograde encounters : global starbursts (? contracting ?)
retrograde -- " -- : nuclear starbursts & AGN fuelling

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

Dynamical Models : Galaxy Interactions

Dynamical models with gas :
Sp + Sp + starburst ➜ E 4
for 1:1 . . . 1:3 mergers with low gas content
Sp + Sp + starburst ➜ S0
disk morphology + E kinematics
for 1:4 . . . 1:10 mergers
(Bournaud et al 2004)



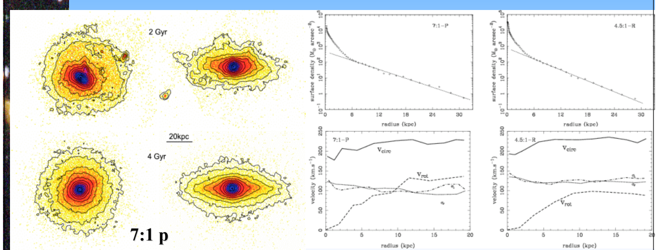


observed e.g. in Arp 214 and Arp 224
(Jog & Chitre 2002)
Sp + Sp + starburst ➜ Sa
disk morphology + disk kinematics
for 1:1 mergers with high gas content
(Springel & Hernquist 2005)

Dynamical Models :Galaxy Interactions

Sp + Sp + starburst ➜ S0

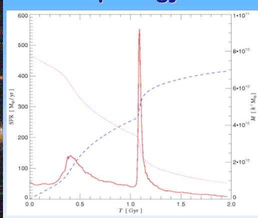
disk morphology + E kinematics

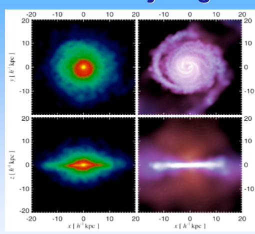


(Bournaud, Combes & Jog 2004)

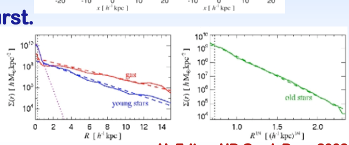
Dynamical Models : Galaxy Interactions

Gas rich : Sp + Sp + starburst ➜ Sa
disk morphology + disk kinematics for young stars & gas





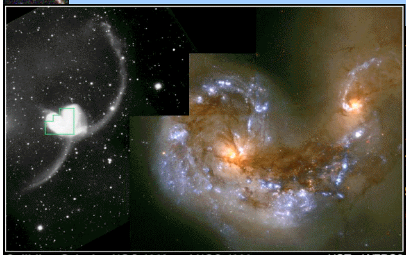
Bulge = stars from 1. burst.
Disk rebuilt from gas surviving strong burst & subsequent SF
(Springel & Hernquist 2005)



Interacting Galaxies & Mergers

Galaxy interactions/mergers trigger strong starbursts if 1 or 2 of the galaxies are gas-rich

e.g. spiral – spiral mergers (NGC 4038/39 = Antennae, NGC 7252, . . .)



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

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Galaxy Interactions & Starbursts

Starbursts in giant interacting galaxies :

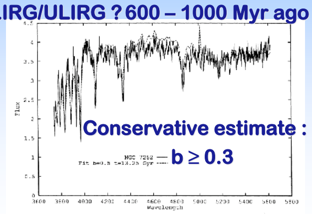
Evol. Synthesis modelling → SFR ~ 30 – 1000 $M_\odot$/yr,

→ post - starbursts b~0.3 – 0.5 (FvA & Gerhard 1994a, b)

E.g. NGC 7252 : bright Sc-Sc Merger (HI in Tidal Tails)

Strong Balmer abs. lines --> Strong global starburst R >10 kpc

LIRG/ULIRG ? 600 – 1000 Myr ago



Conservative estimate : $b \geq 0.3$

Star Formation Efficiency SFE := M_{stars} / $M_{gas} \geq 0.4$

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A model for NGC 7252

Start from broad band SED in UBVRI :
comparison with grid of starburst models -> box in parameter space

Additional pieces of information:
- length of tidal tails / typ. rotation velocity ~ dynam. age of interaction
- HI in both tidal tails : 2 gas-rich spirals ~Sc
- both tails of similar length : both spirals of sim. mass
- very high luminosity : both Scs very bright

Within box of parameter space: detailed comparison with spectral properties

strong Balmer absorption lines : strong starburst 600 – 1000 Myr ago

metal lines : (0.5 – 1) $Z_\odot$

(Fritze – v. A. & Gerhard 1994a, b)

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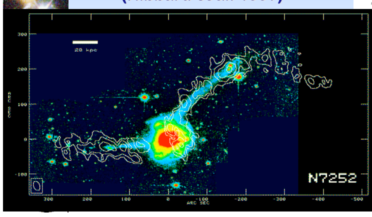
Galaxy Interactions & Starbursts

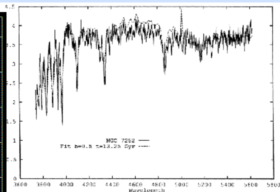
spectral modelling for NGC 7252 → residual SFR ~ 3 $M_\odot$/yr
powered by HI falling back from tidal tails (~50%) and by gas restored from burst stars (~50%)
- emission component in Hβ absorption line
- IUE spectrum + ROSAT data : SF but no AGN

HI falling back from tails for >3 Gyr

➜ HI disk + SF ➜ stellar disk : S0 or Sa (spec + morph)

(Hibbard et al. 1997)





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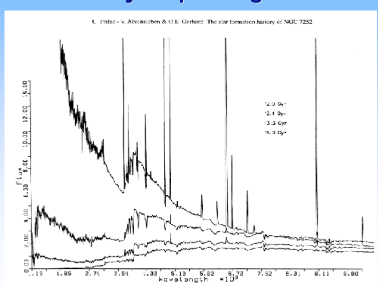
A model for NGC 7252

Future evolution :
will reach E/S0/Sa galaxy colours & spectra within 3 – 5 Gyr depending on future SFR evolution



(Fritze & Gerhard 1994 b)

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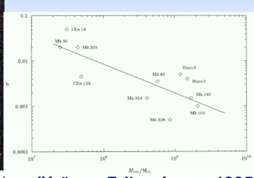
Interacting Galaxies & Mergers

Burst strengths in isolated dwarf and interacting massive galaxies :
★ NGC 7252



(Krüger, Fritze, Loose 1995)

can SF process be the same in isolated dwarf & major merger starbursts ?

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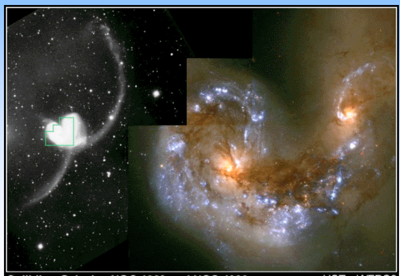
Luminous InfraRed Galaxies (LIRGs) (e.g. Antennae)

$L_{FIR} \sim 10^{10} - 10^{11}\ L_\odot$

= global starbursts in giant gas-rich mergers

→ SFR ~ 30 . . . . 300 $M_\odot$/yr



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

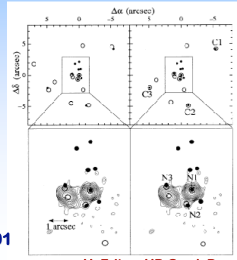
Ultra Luminous InfraRed Galaxies (ULIRGs)

(e.g. Arp 220)

$L_{FIR} \sim L_{bol} \sim 10^{12} - 10^{13}\ L_\odot$ $A_V \sim 30$ mag

= nuclear starbursts in giant gas-rich mergers

→ SFR ~ 300 . . . . > 1000 $M_\odot$/yr



Shioya+2001

Star Formation Efficiencies

Star **F**ormation **E**fficiency SFE := M_{stars} / M_{gas}

Global Scale

Spiral galaxies :	SFE ~ 0.1 – 3 %
Irregular galaxies :	SFE ~ 0.1 – 3 %
Starbursts in dwarf galaxies :	SFE ~ 0.1 – 3 %
in giant interacting galaxies :	SFE ~ 10 – 50 %

10-300 pc scale

Ultra Luminous IR Galaixes : ULIRGs : SFE ~ 30 – 90 %

Small Scale

Milky Way Molecular Clouds : SFE ~ M(MC core) / M(MC) ~ 0.1 – 3 %

Molecular Clouds & SF Processes

Normal galaxies (Spirals, Irrs) :

MC collapse → SFR

MC mass spectrum

= power law : m ~ -1.7 . . . . -2

observed + okay w. supersonic turb.+gravity

≃ MC core mass spectrum

≃ open star cluster mass spectrum

Interacting galaxies :

MC – MC collisions enhanced → SFR ↗

MCs shock compressed by high ambient pressure

→ SFE ↗

$P_{ISM} \sim (3-4)\ P_{MC}$ → SFE ~ 0.7 – 0.9 !

(Jog & Das 1992, 1996)

Molecular Cloud Structure

CO(1-0) traces molecular gas at n≥ 100 cm-3
HCN(1-0) traces molecular gas at n≥ 30000 cm-3
CS(1-0) traces molecular gas at n~100000 cm-3

Small Scale

Milky Way Molecular Clouds :

L(HCN,CS) / L(CO) ~ 0.1 – 3 %
~ M(MC core) / M(MC)

10-300 pc scale

Ultra Luminous IR Galaixes = massive gas-rich mergers :

L(HCN,CS) / L(CO) ~ 30 – 100 %
~ M(MC core) / M(MC)

Molecular Cloud structure in ULIRGs very different from Milky Way

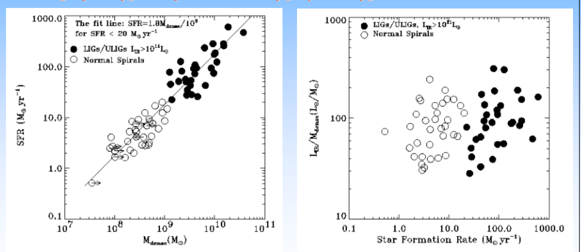
Can the SF process be the same ?

Molecular Cloud Structure & SF

For all galaxies (Spirals . . . ULIRGs) :

tight correlation SFR [L(FIR)] — M(MC cores)[L(HCN)]

SFR [L(FIR)] / M(MC cores)[L(HCN)] ~ const. =: SFE



(Gao & Solomon 2004, Solomon et al. 1992)

For all galaxies (BCDs . . . Spirals . . . ULIRGs) :

SFE ~ M(MC core) / M(MC)
~ L(HCN,CS) / L(CO)

Schmidt law (1959) : (Kennicutt 1998 : n ~1.4)
SFR density ~ gas (HI) density ** n,
SFR density ~ gas (CO) density ** n
n~1 for spirals . . . n~2 for ULIRGs
(over 5 orders in gas surface density & 6 orders in SFR density)

Schmidt law :
SFR density ~ gas (HCN,CS) density ** n
n=1 for all galaxies (spirals . . . ULIRGs)
(Gao & Solomon 2004)

Timescale & Efficiency for SF are set by transformation
low ➜ high density gas : HI, CO ➜ HCN, CS

➜ Importance of multi – phase ISM in dynam. models !

Starbursts in Interacting Galaxies

Pixel-by-pixel analyses of Tadpole & Mice galaxies
SF in these interacting & starburst galaxies is
star cluster formation to a large extent

70% of U - light is from star clusters
40% of I - light

Star cluster formation = the dominant mode of SF

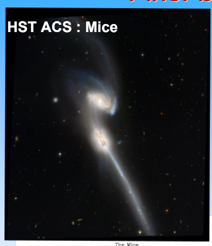
even in the expanding low-density tidal tails, where the
HI surface density is far below the critical threshold* !

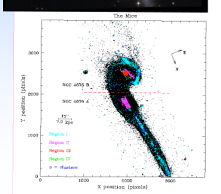
With SFR ↗ rel. amount of SF into star clusters ↗
rel. amount of SF into massive compact
long-lived clusters ↗

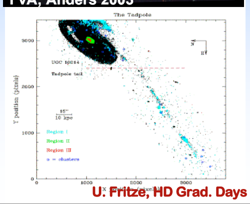
Feedback from strongly clustered SF
≠ feedback from lower-level smooth SF

*critical HI surface density below which SF is suppressed in normal spirals (Kennicutt's threshold)

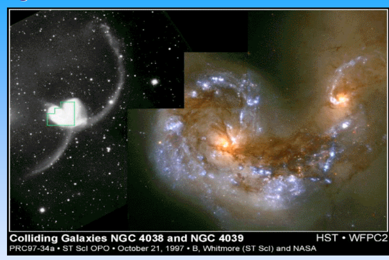
Starbursts in Interacting Galaxies
Pixel-by-pixel analyses







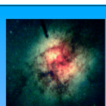
Galaxy Interactions & Cluster Formation



Strong starburst → formation of thousands of bright
star clusters from gas pre-enriched in the spirals.
High star formation efficiency → clusters massive,
compact & strongly bound,
long-lived proto-Globular Clusters!
(Burkert, Brown, Truran 96) η ≥10 - 30 % : Globular Clusters

Secondary GCs = eternal tracers of violent SF epoch

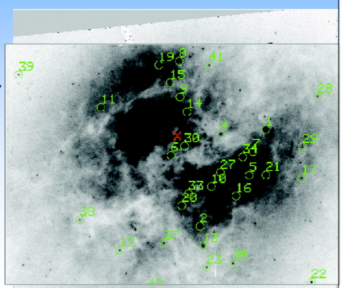
Star Clusters in Arp 220



Wilson+06 ACS HRC : UBVI
206 star cluster candidates
strongly concentrated to the centre
of the nearest ULIRG Arp 220

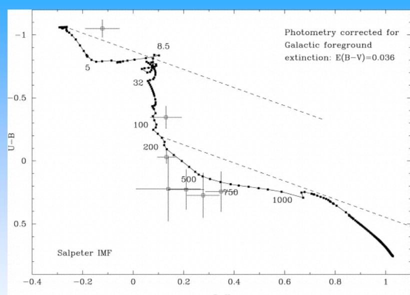
2 age groups of
star clusters :
<10 Myr and ~300 Myr

many clusters with
masses > 10^6 $M_\odot$



Star Clusters in Arp 220

(Wilson+06)



Star Clusters in Arp 220

TABLE 3
MASSES AND AGES FOR CLUSTERS IN ARP 220

ID	V	σ_V	$B-V$	σ_{B-V}	$U-B$	σ_{U-B}	$V-H$[a]	σ_{V-H}[a]	Age (Myr)	$E(B-V)$	Mass ($M_\odot$)	Scoville ID[b]
1	22.515	0.019	1.227	0.037	...	...	3.09	0.08	1–3[c]	1.48	$(0.6–1.2) \times 10^7$	1
2	23.240	0.039	1.152	0.083	...	...	2.57	0.25	1–3[c]	1.27	$(2–4) \times 10^6$	2
3	22.611	0.022	0.168	0.036	−0.005	0.050	...	...	200	0	1.5×10^6	...
4	24.350	0.074	1.672	0.196	...	...	<3.40	...	1–3[c,d]	1.71	$(2–4) \times 10^6$	3
5	23.917	0.041	0.808	0.071	...	...	3.15	...	1–3[c,e]	0.96	$(2–4) \times 10^6$	5
11	24.432	0.073	1.017	0.143	...	...	2.72	...	1–3[c,f]	1.33	$(0.8–1.6) \times 10^6$	7
12	25.960	0.188	...	...	...	...	4.71	...	1–3[c]	2.13	$(2–4) \times 10^6$	8
18	24.040	0.041	0.384	0.061	0.269	0.158	...	...	500	0	7×10^5	...
20	25.049	0.117	1.339	0.249	...	...	3.58	...	1–3[c]	1.68	$(1–2) \times 10^6$	6
24	24.132	0.041	0.313	0.064	0.299	0.177	...	...	400	0	5×10^5	...
25	24.248	0.055	0.246	0.069	0.253	0.158	...	...	500	0	5×10^5	...
31	24.203	0.044	0.166	0.062	−0.320	0.088	...	...	70	0	2×10^5	...
62	24.976	0.087	0.175	0.127	0.248	0.255	...	...	400	0	3×10^5	...
86	24.502	0.047	−0.086	0.067	−1.025	0.069	...	...	1–3[c]	0.15	$(2.5–5) \times 10^4$	...

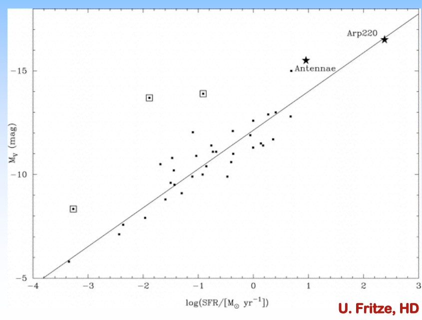
NOTES.—A distance to Arp 220 of 77 Mpc is assumed throughout. Masses are derived from Bruzual & Charlot (2003) models assuming a Salpeter initial mass function and a standard reddening law (see text).
[a] NICMOS 1.6 μm photometry from Scoville et al. (1998; clusters 1, 2, and 4) and Scoville et al. (2000; clusters 5, 11, 12, and 20).
[b] Cluster identification number from Scoville et al. (1998).
[c] It is impossible to distinguish between these two young ages; the older age of 3 Myr corresponds to the smaller mass.
[d] Since this cluster has only an upper limit to $V-H$, its reddening was estimated from the $V-I$ color.
[e] Another possible solution is an unreddened 13 Gyr cluster with a mass of $1 \times 10^7 M_\odot$. A third possible solution is a 300 Myr cluster with $E(B-V) = 0.56$ and a mass of $3 \times 10^6 M_\odot$.
[f] Another possible solution is an unreddened 13 Gyr cluster with a mass of $7 \times 10^6 M_\odot$.

UH

Star Clusters in Arp 220

(Wilson+06) SCs in Arp 220 follow the trend :

the higher the SFR of the galaxy, the brighter is the brightest star cluster

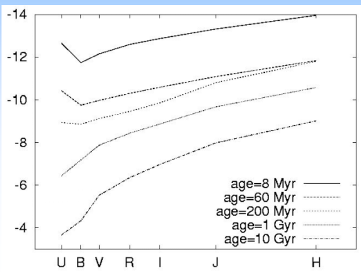


UH

Analysis of Star Cluster Systems : SSPs

Grid of Spectral Energy Distributions

SSPs : 5 metallicities −1.7 ≤ [Fe/H] ≤ +0.4
4000 ages 4 Myr . . . . . 16 Gyr
20 extinction values 0 ≤ E(B-V) ≤ 1
(Starburst extinction law → Calzetti et al. 2000)



400.000

Spectral
Energy
Distributions

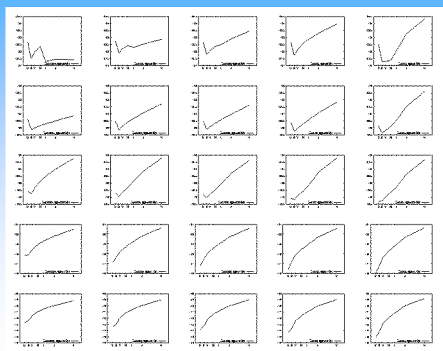
e.g. $Z_\odot$, $E_{B-V} = 0$

↕ mass

UH

Analysis of Star Cluster Systems

Multi–band photometry - Grid of Models (GALEV)



Spectral
Energy
Distributions

8 Myr
60 Myr
200 Myr
1 Gyr
10 Gyr

Z=0.0004 Z=0.004 Z=0.008 Z=0.02 Z=0.05 $E_{B-V} = 0$

UH

AnalySED* : Star Cluster SED ↔ Model SEDs

(Anders+04a, b)

- $\chi^2 = \Sigma_\lambda (m^\lambda_{obs} - m^\lambda_{model})^2 / \sigma_{obs}^2$
- probability for each model SED p(n) ~ exp (- χ^2)
- normalise to Σ_n p(n) = 1 (best fit model SED := highest p)
- sum models with decreasing probabilities until Σ_n p(n) = 0.68
  → ± 1 σ uncertainties

➔

- ★ ages
- ★ metallicities ± 1 σ uncertainties
- ★ extinction values
- ★ masses

for all individual SCs with 3 (or 4) passbands (U/B . . . K)

artificial SC tests : ages [Fe/H]

UH

Artificial star cluster tests w. model & obs. uncertainties

UV/U important for age dating of YSCs
NIR important for metallicities

YSCs (dusty galaxies) : 4 passbands (UV/U, . . ., H or K)
GCs (dustfree galaxies) : 3 passbands (U/B, . . ., H or K)

UV/U + opt. + NIR : disentangle ages & metallicities
get ✩ ages to Δage/age ≤ 0.3
✩ metallicities to +/- 0.2 dex

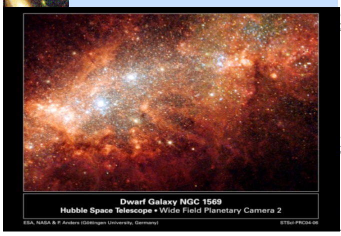
(Anders+04a, de Grijs+03)

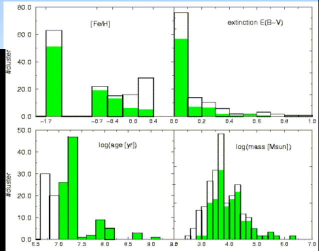
UH

Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

NGC 1569 dwarf starburst galaxy, 3 Super Star Clusters + 166 young star clusters

- ➜ metallicities
- ➜ ages — for individual SCs (Anders+04a,b)
- ➜ extinction values — ± 1σ uncertainties
- ➜ SC masses





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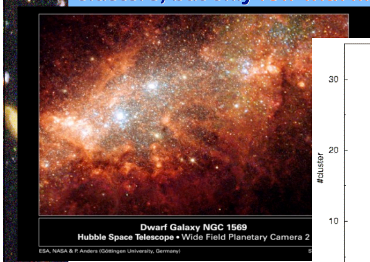
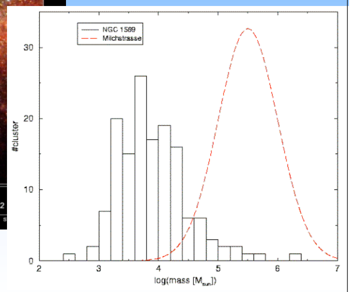
Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

NGC 1569 dwarf starburst galaxy formed 169 young star clusters, but only few with masses of Globular Clusters



(Anders & FvA 03, Anders et al. 04a, b)



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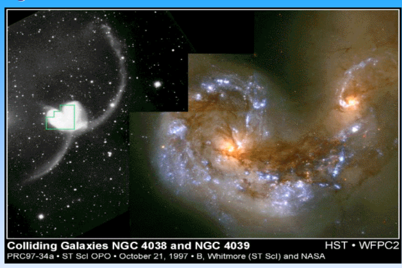
Galaxy Interactions & Cluster Formation



Young star clusters in Antennae have masses 10^3 - 10^7 $M_\odot$, radii 1 - 20 pc. No dichotomy between open clusters and globular clusters, full continuum instead.

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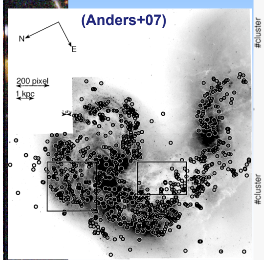
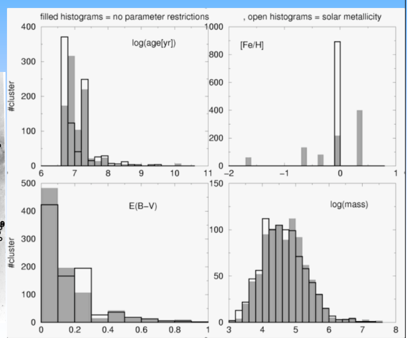
The Star Cluster System in the Antennae

(Anders+07)

ongoing starburst in NGC 4038/39 forms a rich YSC system, > 1500 YSCs





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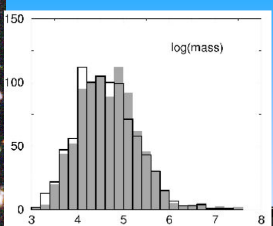
Interacting Galaxies & Globular Cluster Formation

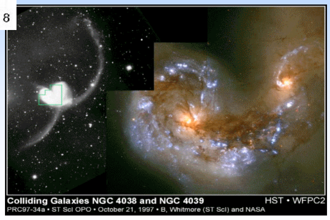


Strong Starburst
→ strong star cluster formation

ages < 2 · 10^8 yr
masses $10^3 \ldots 10^7$ $M_\odot$
radii 4 -15 pc
[Fe/H] ~ 0

? long-lived -- shortlived ?
(Fritze 98, 99, 04, Anders+07)

Most YSCs in the Antennae have masses & radii typical for GCs
➜ they will probably survive for many Gyr, give testimony of the starburst/merger



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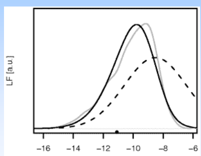
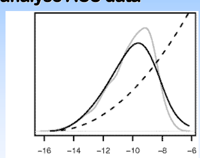
A Closer Look at the Antennae's SC System

The SC Luminosity Function (LF) has a turnover to 99.5 % significance! * (Anders+07)

LF ➜ MassFunction difficult
? how to translate completeness limit in luminosity into completeness limit in mass ?
indication for turn-over in MF of YSCs in diff. age bins
? statistical significance ? ➜ analyse ACS data



Gauss
Power law



Evidence : SFR(➜ massive SCs) > SFR(➜ low-mass SCs)

No discrimination for individual YSCs :
Young GCs — Young Open Clusters

M(YSC) vs. $R_{1/2}$: scatter plot

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* Background ....

The Luminosity Function and the Mass Function of Milky Way (& other galaxies') old Globular Cluster systems show a turnover,

while for young open clusters, for molecular clouds and molecular cloud cores, power laws are observed.

??? Is the turnover for the old GCs a result of secular evolution ???
??? or did the GC system already show a turnover when it was young ???

Ongoing debate among theorists: N-body models for survival and destruction of GCs in a galaxy potential.

Some speculation ....

If the turnover in the LF would reflect a turnover in the MF, this would

☛ tie in nicely with Parmentier & Gilmore's 05, 07 empirical results :
MW GC system initially had a mass spectrum with turnover around 10^5 $M_\odot$

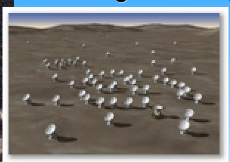
☛ indicate that the MF of the molecular clouds in the massive gas-rich Antennae merger (LIRG) is different from situation in undisturbed spirals, dwarf galaxy starbursts

(as expected due to pressure effects)

➜ prediction to be tested with ALMA

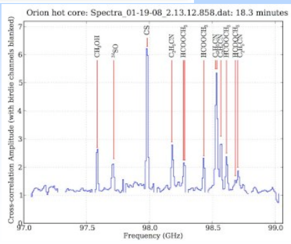
Atacama Large Millimeter Array : ALMA

➜ high sensitivity & high spatial resolution observations of molecular gas

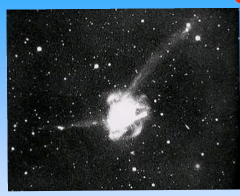


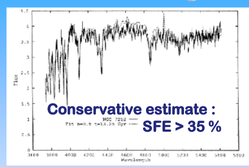
80 antennas 5000m

Jan.08
1. interfer.
spectrum



Globular Cluster Formation in Interacting Galaxies & Mergers





NGC 7252 : Post – Starburst : SFE > 30 %
(cf. SFE ≪ 3 % in normal galaxies)
hundreds of star clusters ages ~ 0.6 – 1 Gyr
masses $10^4 \ldots 10^6$ $M_\odot$, radii ~ 4 pc, Z = (0.5 . . . 1) $Z_\odot$,
long-lived : young Globular Clusters
N(young GCs) ~ N(old GCs) ! *

Secondary GCs = eternal tracers of violent SF epoch.

* Background :

Globular Cluster specific frequency (S_{GC} or T_{GC}) := N_{GC} per galaxy luminosity or mass

Ashman & Zepf (1993) : $\langle T_{GC}\rangle_E = 2 \langle T_{GC}\rangle_{Sp}$
Ellipticals on average have twice the number of GC per unit of mass than spirals

The starburst in the massive gas-rich spiral-spiral merger NGC 7252 formed many new GCs !
(ok with SF efficiency)

Enough survived the first 600 - 900 Myr to fulfill

$\langle T_{GC}\rangle_E = 2 \langle T_{GC}\rangle_{Sp}$ (Fritze & Burkert 95, Schweizer 02)

Masses ~ $10^5 - 10^6$ $M_\odot$ W3: $(7 - 8)10^7$ $M_\odot$, (Maraston+01, 04)

(spectroscopy and multi-band photometry) Z ~ (0.5 - 1) $Z_\odot$

Cosmological Importance of Galaxy Interactions & Starbursts

Hierarchical structure formation scenario :

Galaxies build up continuously from smaller building blocks ± starbursts !

Galaxy interactions much more frequent in the past & much stronger, galaxies more gas-rich

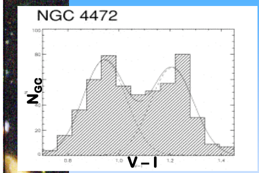
Key role of (Globular) Star Clusters
= eternal tracers of violent star formation episodes

SC analysis 1-by-1 : age & metallicity distributions, much better than integrated light ! (FvA 98, 99, 04)

Multi-band Photometrie : HST (+ ground) UBVRI+NIR

Globular Cluster Analyses

ACS Virgo Cluster Project : B – I distributions of 100 GCSs in E/S0s (Peng+06)



many bimodal :
blue peak : universal, old+metal-poor
red peak : variable, younger ± more metal-rich ?

Optical colors degenerate in age & metallicity
☛ optical + NIR colors largely resolve degeneracy

e.g. V – I = 1.2 2 Gyr, [Fe/H]= +0.4 V – K = 3.5
V – I = 1.2 13 Gyr, [Fe/H]= – 1.7 V – K = 2.3
(Fritze 04)

with additional K – imaging & AnalySED
➜ GC ages to Δ age/age ~ 0.2
➜ GC metallicities to ~ 0.2 dex

Globular Cluster Age & Metallicity Distributions

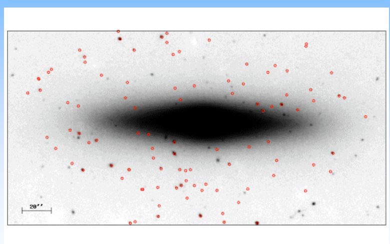
= key tracers of their parent galaxy's (violent) SFH & metal enrichment histories over cosmological lookback times, i.e. back to the very onset of SF in the Early Universe.

Before we can also use them to study their parent galaxy's mass assembly histories, we must understand the relative amount of SF that goes into the formation of massive, strongly bound, long-term stable SCs and its dependence on galaxy, interaction & starburst properties ➜ study major mergers/minor accretions, big/dwarf galaxies, gas-rich/gas-poor

Astro-archeology

Globular Cluster Age & Metallicity Distributions

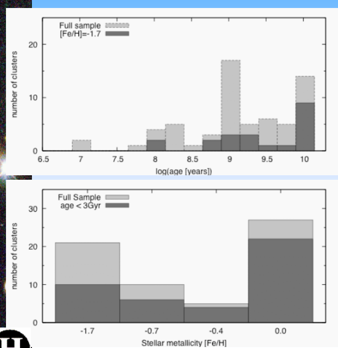
GC population in S0 NGC 4570 : (Kotulla & Fritze 08)



HST ACS g, z (VCS)
+ NTT-SOFI K to 21.3 Vega mag

Globular Cluster Age & Metallicity Distributions

NGC 4570 : (Kotulla & Fritze 08)



GC age distribution
➜ when a starburst occurred

GC metallicity distrib.
➜ what happened minor accretion or major merger

Star Clusters = Simple Stellar Populations
: easy to model & easy to analyse 1 – by – 1
: accessible via multi-band photometry to Virgo cluster distances & beyond

Ages & metallicities of young SC populations
= tracers of recent/ongoing SFH in galaxies dust !

Ages & metallicities of GC populations
= tracers of violent SFHs over t_{Hubble} ~ no dust !
(SCs better than integrated light & complementary to high-z studies!)

Key : ages & metallicities from SEDs U B V R I J H K

color → metallicity only at fixed age
color → age only at given metallicity
SED → age & metallicity (& dust) independently