Interacting Galaxies

Observations & Theory

Local Universe to High Redshift

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SS 2008 Universität Göttingen

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Local Universe to High Redshift

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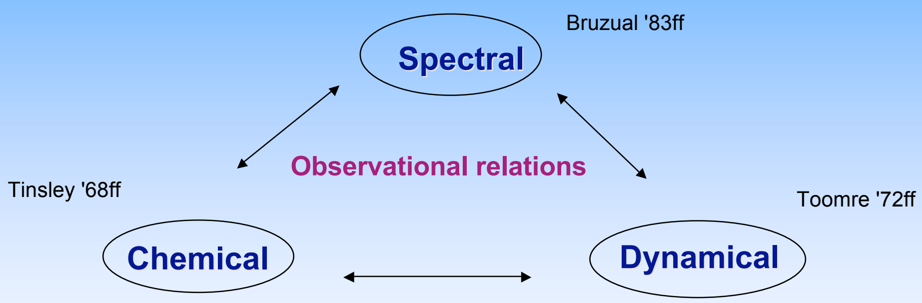
Dates: 17.4. Overview & basic concepts
(1.5. Holiday)
(15.5. HST Panel meeting)
22.5. Dyn. models & obs. examples
19.6. (5.6.) Star Bursts & Star Cluster Formation
19.6. ULIRGs & SCUBA galaxies
3.7. Galaxy transformation in clusters
17.7. Interactions @ high redshift

Dynamical Evolution of a Galaxies

= 3rd aspect of galaxy evolution



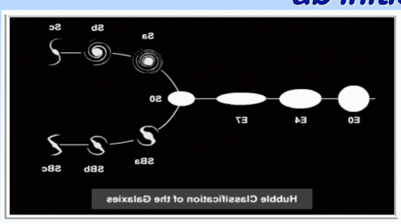
S : formation & evolution of stars +/- gas +/- dust
C : formation & nucleosynthesis of stars; infall/outflow of gas
D : internal & external gravitation, stars + gas + DM

Galaxy Interactions

$\langle star \leftrightarrow star \rangle \simeq 10^7 \langle \oslash_{\star} \rangle$
$\langle galaxy \leftrightarrow galaxy \rangle \simeq 40 \langle \oslash_{gal} \rangle$

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

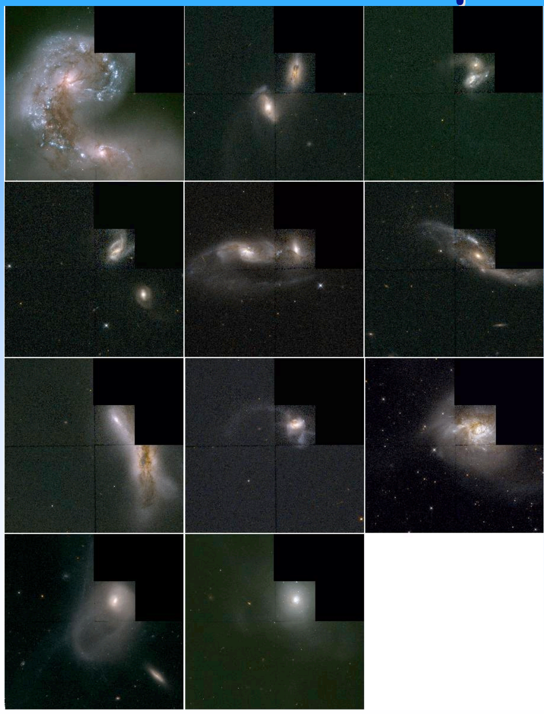
Toomre & Toomre (1972): Hubble sequence not *ab initio ad infinitum*



☛ Morphological transformations

spiral + spiral ® E/S0
disk + dwarf galaxy ➜ bulge (e.g. Sd + dwarf ➜ Sb, Sa)

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

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

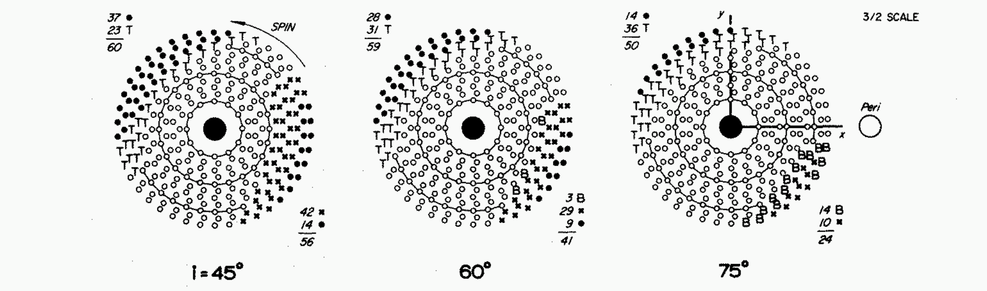


FIG. 15.—Scorecards of tail-making and accretion for three (i = 45°, 60°, and 75°) inclined ω = 0° parabolic passages of a companion of equal mass. The open symbols represent test particles retained by the primary mass point, crosses are those captured by the intruder, T's are nonescaping tail particles 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 $0.6R_{min}$.

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Toomre & Toomre 1972 ff : first numerical modelling

★ slow prograde encounters : strongest tidal forces,

★ tidal forces symetric, 1 tail per disk nicest tails

★ tidal tails develop on t_{dyn}: $l = v_{rot} \cdot t$ after 1st peric.

★ 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

★ violent relaxation : exp. disk ➜ de Vauc. profile E

➜ L-σ relation & fundamental plain relations

★ incomplete : gradients partly survive

★ propagates outward: fall-back of material, few % escape

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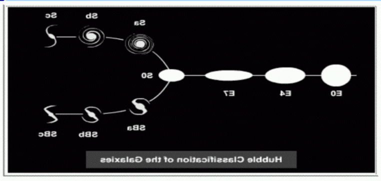
Galaxy Interactions

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 $N \sim 10^5 - 10^6$
disk + bulge + halo

SPH TREE Codes : gas (or Sticky Particles method)

➜ high gas concentrations towards centres

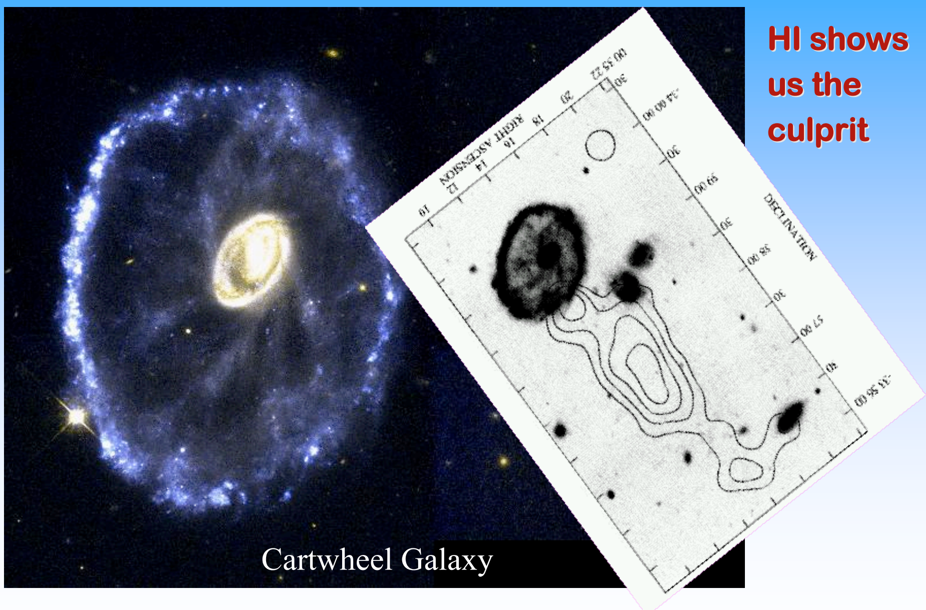
➜ central gas densities ~ stellar central densities of Es ✔
as observed in ULIRGs (= Ultraluminous IR Gals
= advanced stages of gas-rich mergers)

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

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

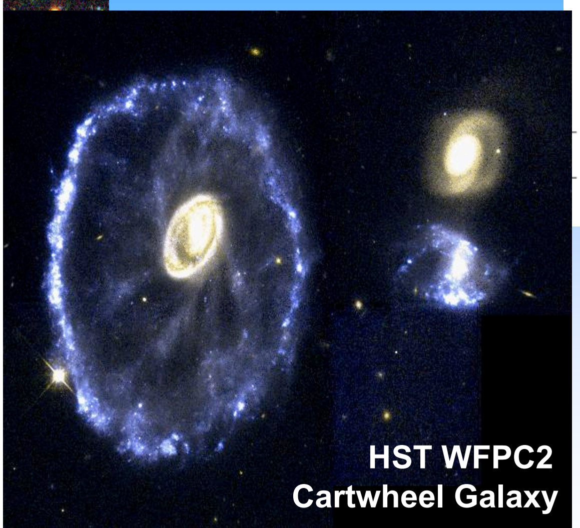
➜ formation of GCs in mergers : GC specific frequency ✔

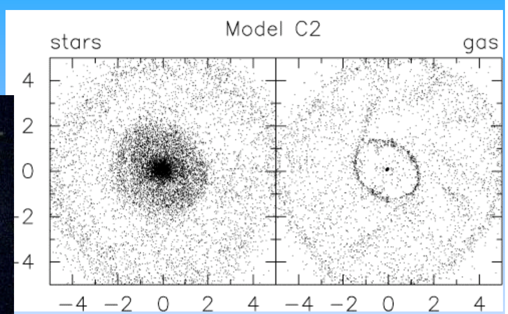
Galaxy Interactions



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

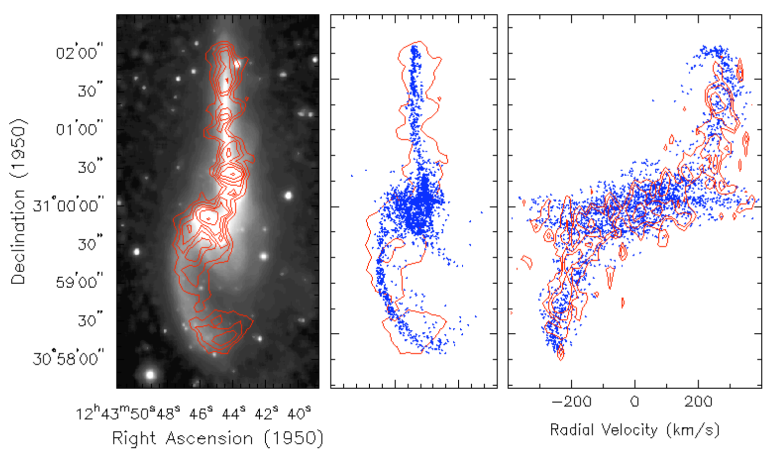
Galaxy Interactions

Barnes & Hibbard 02 : self-consistent numerical modelling for the Mice galaxies (NGC 4676):

Left: optical image and HI contours (red).

Middle: HI contour (red) and N-body model (blue).

Right: position-velocity diagram; HI contours (red) and N-body model (blue).



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Galaxy Interactions

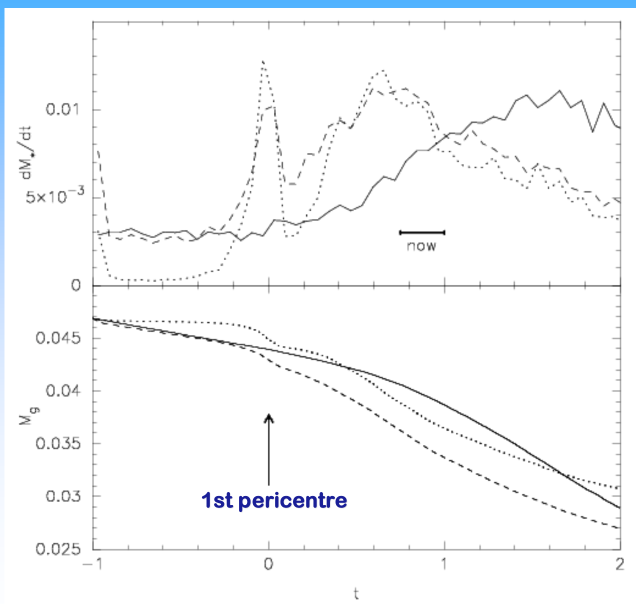
Barnes 04 : numerical modelling for the Mice galaxies

Galaxy Interactions

Barnes 04 : numerical modelling for the Mice galaxies:

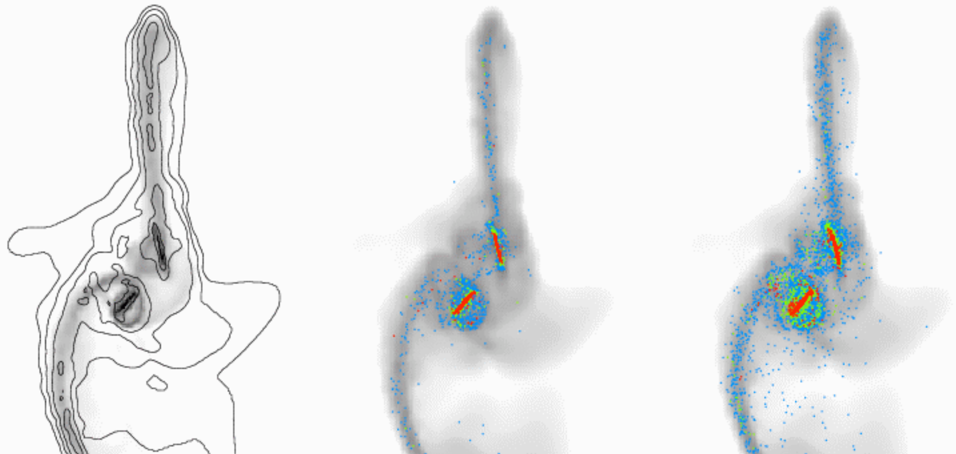
SFR

gas content



Galaxy Interactions

Barnes 04 : numerical modelling for the Mice galaxies



Star formation distribution models of NGC 4676 (Barnes 2004). Left: gas (greyscale) and old stars (contours). Middle: density-dependent SF; old stars (greyscale) and recent star formation (red: youngest, green: intermediate, blue: oldest). Right: weak shock-induced SF.

Dynamical Models & Galaxy Interactions 2008

Modern dynamical models (gas + stars, large particle numbers, high resolution in space & mass) qualitatively confirm all of Toomres' early results for :

- ★ ~ 1:1 mass ratio interactions
- ★ spirals with low gas content

★ Timescales have changed since bulges & DM are included

- ★ bulges stabilize disk (for some time)
- ★ DM halos accelerate merging

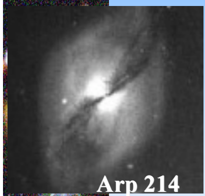
Dynamical Models : Galaxy Interactions

Dynamical models with gas :

Sp + Sp + starburst ➜ E 4

for 1:1 . . . 1:3 mergers with low gas content

Sp + Sp + starburst ➜ S0

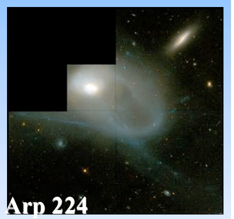


disk morphology + E kinematics

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

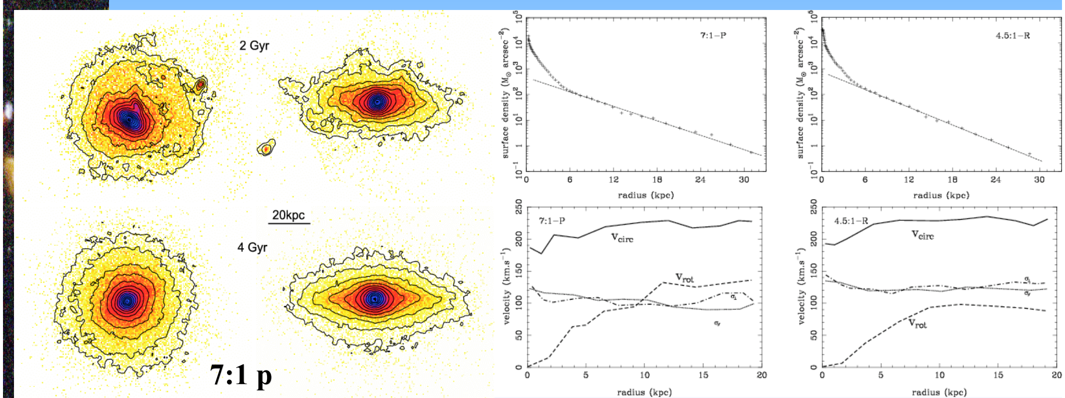
for 1:1 mergers with high gas content

(Springel & Hernquist 2005)

Dynamical Models :Galaxy Interactions

Sp + Sp + starburst ➜ S0

disk morphology + E kinematics

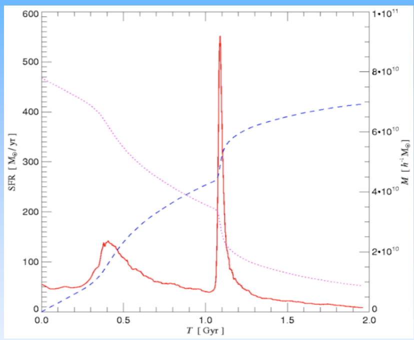


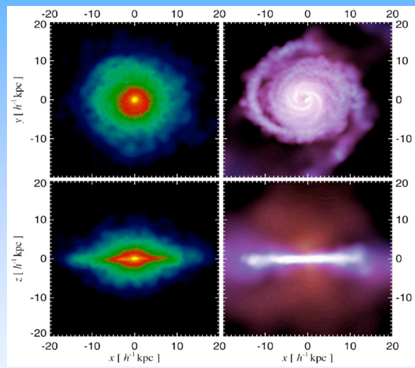
(Bournaud, Combes & Jog 2004)

Dynamical Models : Galaxy Interactions

Gas rich : Sp + Sp + starburst ➜ Sa

disk morphology + disk kinematics for young stars & gas

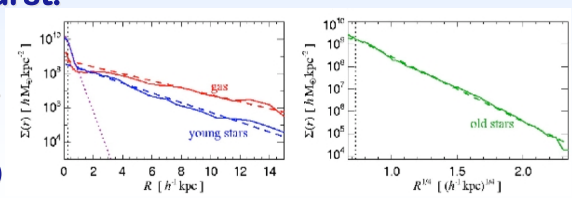




Bulge = stars from 1. burst.

Disk rebuilt from gas surviving strong burst & subsequent SF

(Springel & Hernquist 2005)



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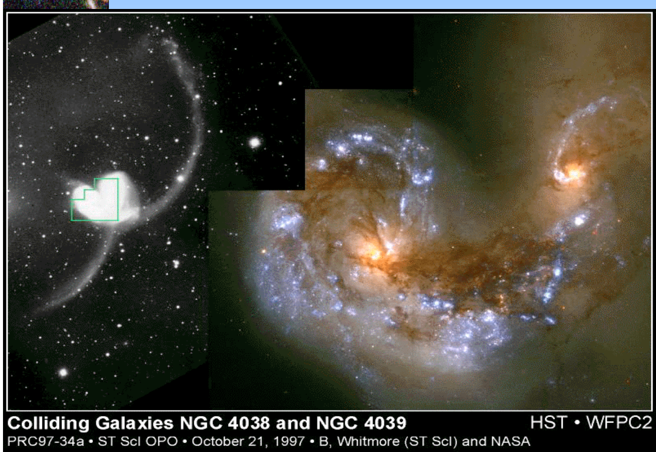
Interacting Galaxies & Mergers

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, . . .)



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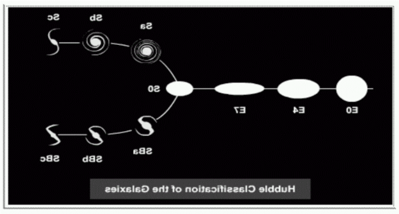
Galaxy Interactions & Starbursts

☛ Morphological transformation

spiral + spiral + starburst → E/S0

Sd + gas-rich/gas-poor dwarf + starburst → Sb, Sa



GALEV :

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

⇒ spectral transformation spiral + spiral + starburst → E

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

Galaxy Interactions & Starbursts

Starbursts in giant interacting galaxies :

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

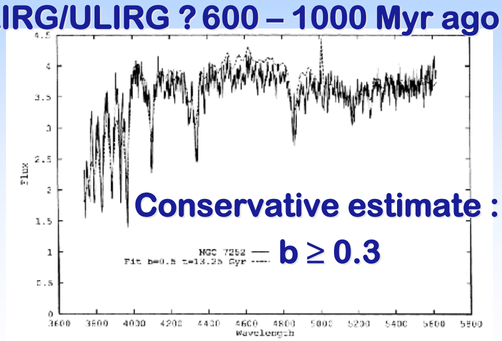
→ post - starbursts b~0.3 – 0.5 (FvA & Gerhard 1994a, b)

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 := $M_{stars} / M_{gas} \geq 0.4$

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 Sc’s 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

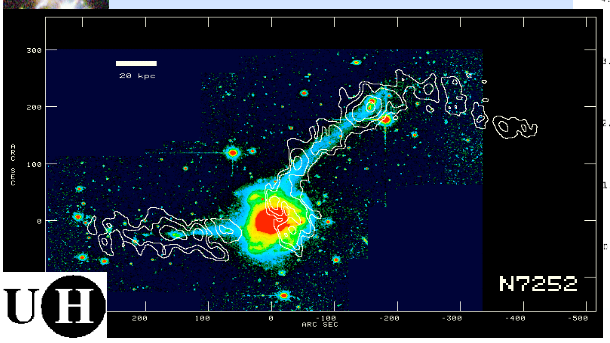
powered by HI falling back from tidal tails (~50%) and by gas restored from burst stars (~50%)

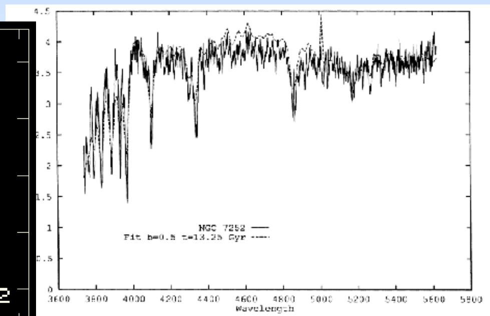
- emission component in Hβ absorption line
- IUE spectrum + ROSAT data : SF but no AGN

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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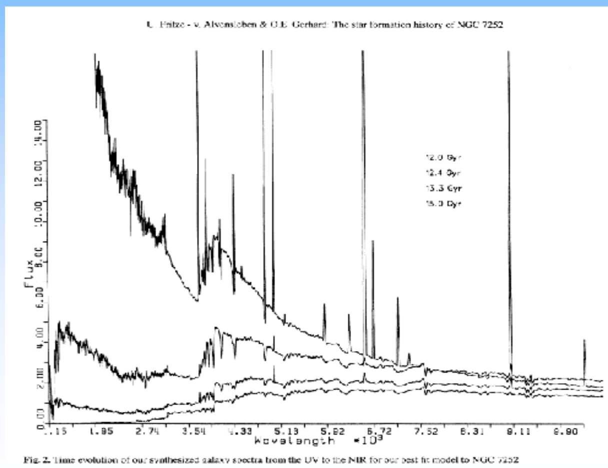
A model for NGC 7252

Future evolution :

NGC 7252 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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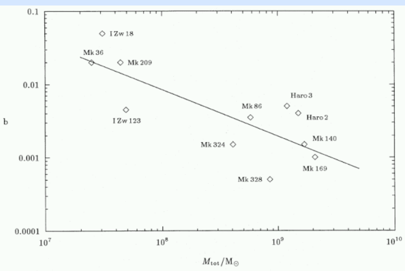
Interacting Galaxies & Mergers

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

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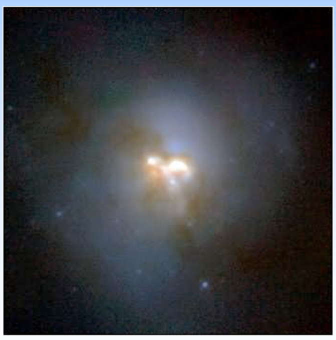
Ultra Luminous InfraRed Galaxies (ULIRGs)

(e.g. Arp 220)

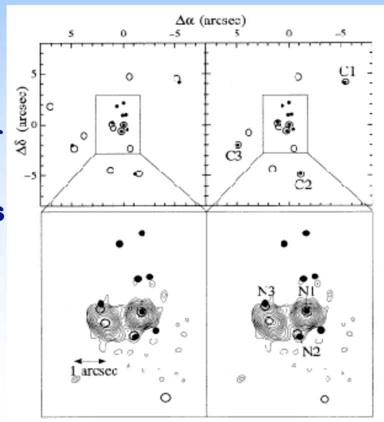
$L_{FIR} \sim L_{bol} \sim 10^{12} - 10^{13}\ L_{\odot}$ $A_V \sim 30$ mag

= nuclear starbursts in giant gas-rich mergers

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



Nuclear star clusters



Shioya+2001

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Star Formation Efficiencies

Star Formation Efficiency 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 %

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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} ~ (3 – 4) P_{MC} → SFE ~ 0.7 – 0.9 !

(Jog & Das 1992, 1996)

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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 ?

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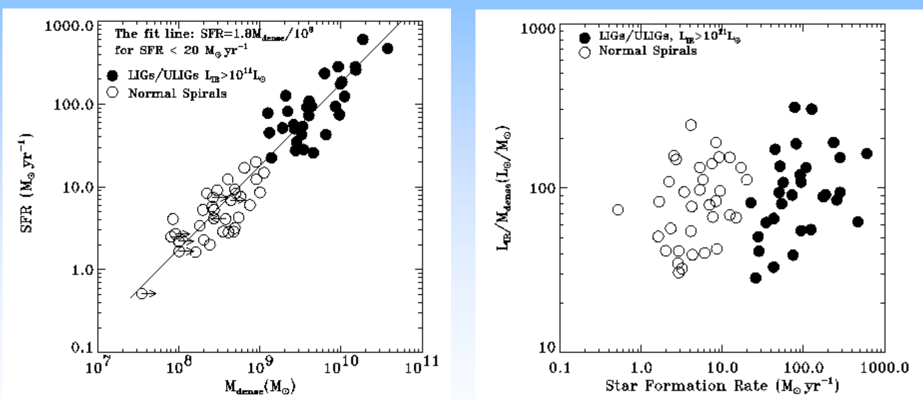
Molecular Cloud Structure & SF

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)

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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

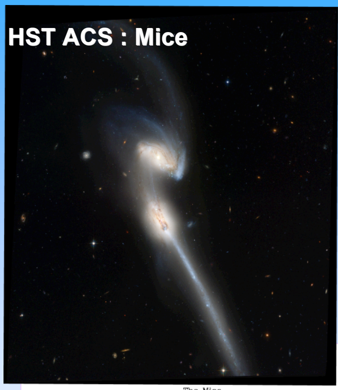
even in the expanding low-density tidal tails, where the
HI surface density is far below the critical threshold* !

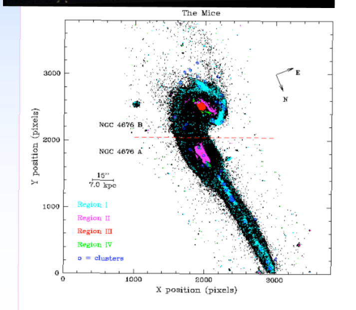
With SFR ↗ rel. amount of SF into star clusters ↗
rel. amount of SF into massive compact
long-lived clusters ↗

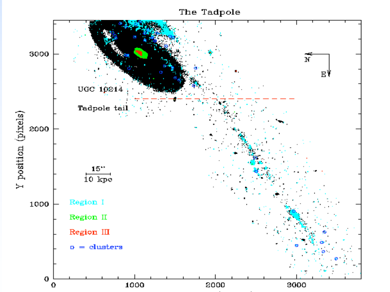
Feedback from strongly clustered SF
≠ feedback from lower-level smooth SF

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

Starbursts in Interacting Galaxies
Pixel-by-pixel analyses







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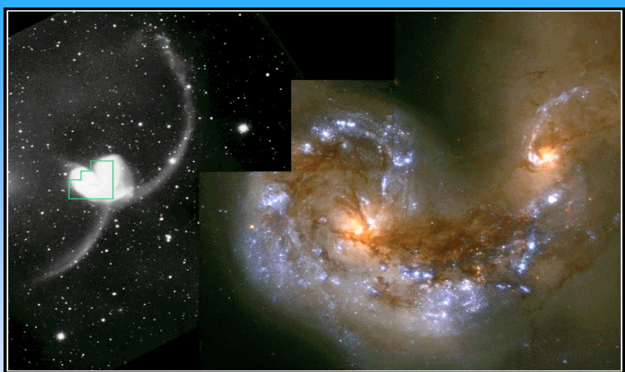
Galaxy Interactions & Cluster Formation



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

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) $\eta \geq 10 - 30\ \%$: Globular Clusters

Secondary GCs = eternal tracers of violent SF epoch

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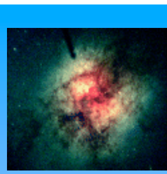
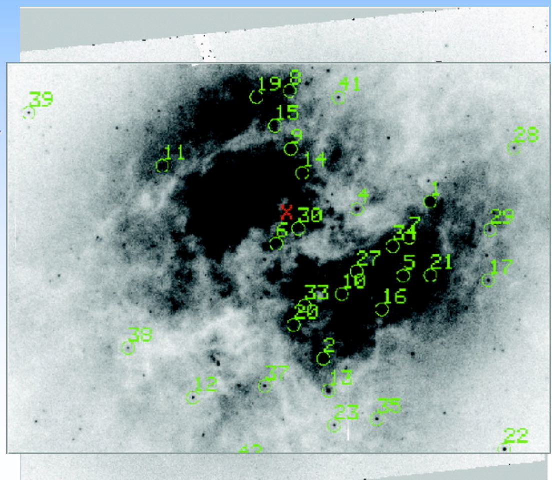
Star Clusters in Arp 220



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

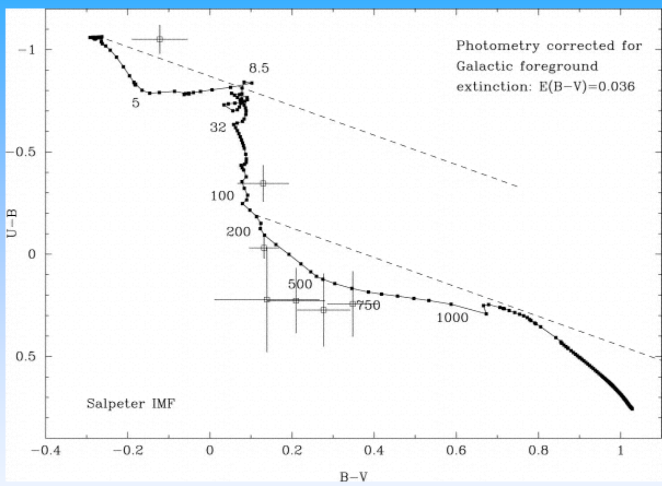
2 age groups of
star clusters :
<10 Myr and ~300 Myr

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



Star Clusters in Arp 220

(Wilson+06)



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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.

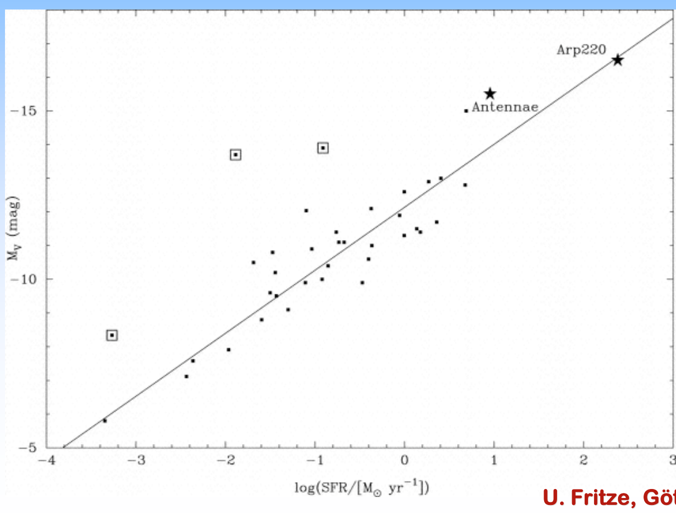
[e] Another possible solution is an unreddened 13 Gyr cluster with a mass of $1 \times 10^7\ M_\odot$. A third possible solution is a 300 Myr cluster with $E(B-V) = 0.56$ and a mass of $3 \times 10^6\ M_\odot$.

[f] Another possible solution is an unreddened 13 Gyr cluster with a mass of $7 \times 10^6\ M_\odot$.

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



Analysis of Star Cluster Systems : SSPs

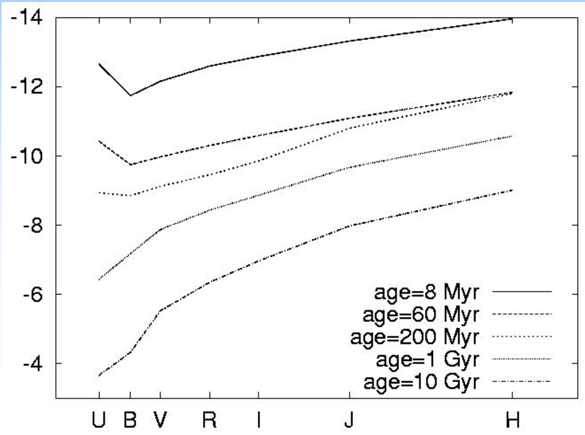
Grid of Spectral Energy Distributions

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

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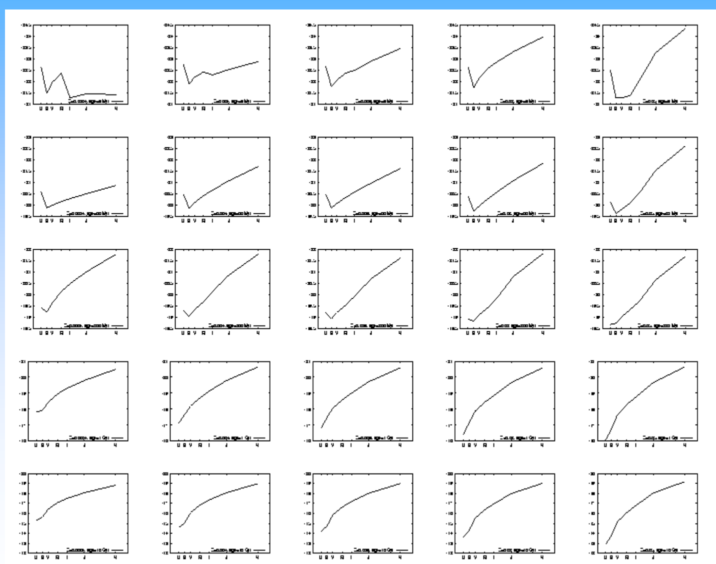
UH

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

$E_{B-V} = 0$

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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 $p(n) \sim \exp(-\chi^2)$
- normalise to $\Sigma_n \, p(n) = 1$ (best fit model SED := highest p)
- sum models with decreasing probabilities until $\Sigma_n \, p(n) = 0.68$

→ ± 1 σ uncertainties

➔

- ★ ages
- ★ metallicities
- ★ extinction values
- ★ masses

± 1 σ uncertainties

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

artificial SC tests : ages [Fe/H]

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 $\Delta age/age \leq 0.3$

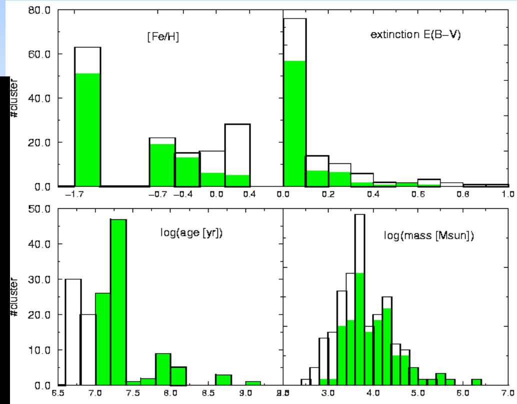
☆ metallicities to +/- 0.2 dex

(Anders+04a, de Grijs+03)

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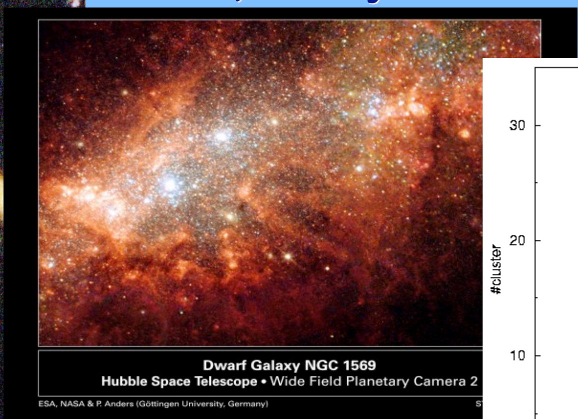
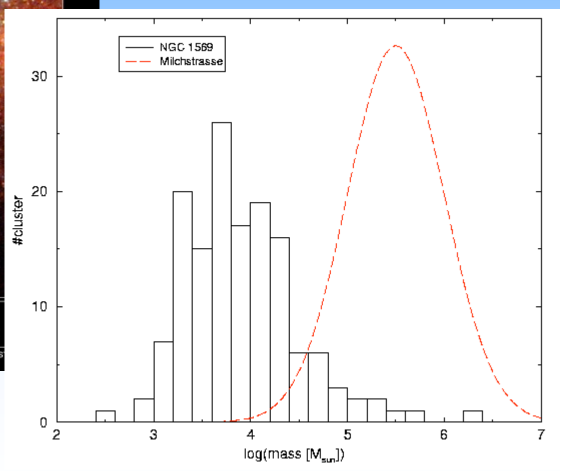
Analysis of Star Cluster Systems
Multi–band Photometry - Grid of Models

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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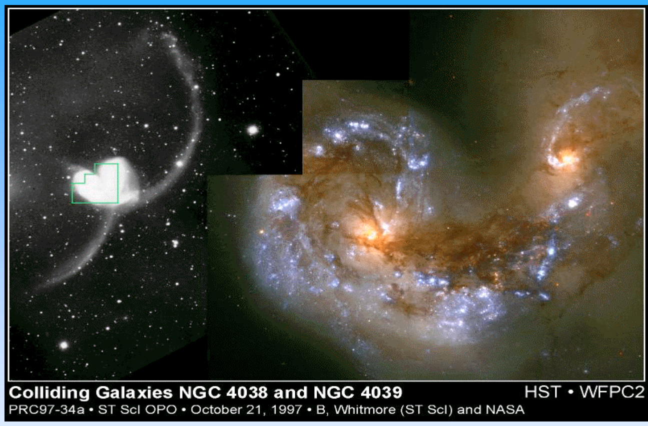
Galaxy Interactions & Cluster Formation



> 1500 young star clusters in Antennae :
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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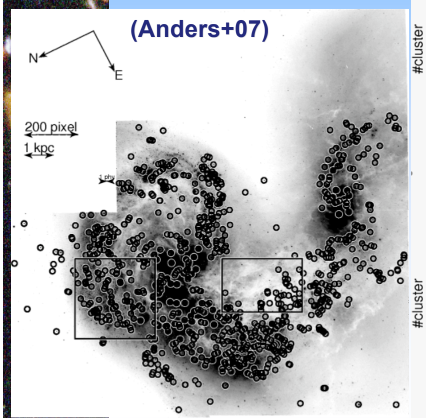
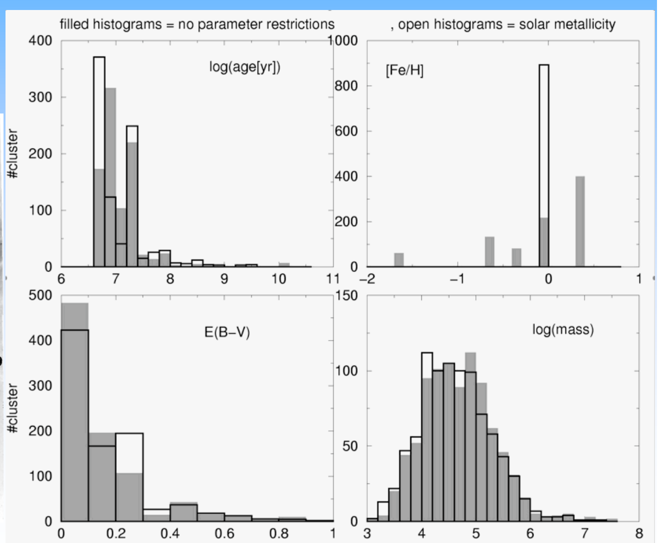
The Star Cluster System in the Antennae

(Anders+07)

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





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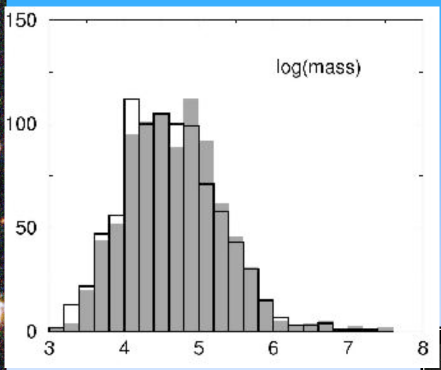
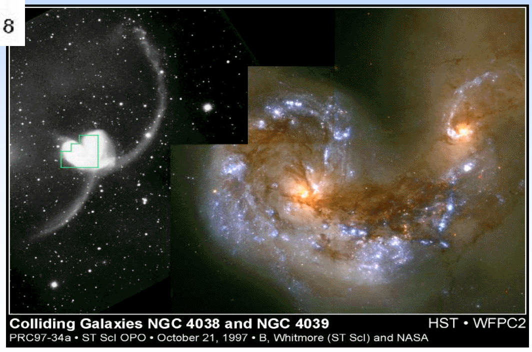
Interacting Galaxies & Globular Cluster Formation



Strong Starburst
→ strong star cluster formation

ages < $2 \cdot 10^8$ 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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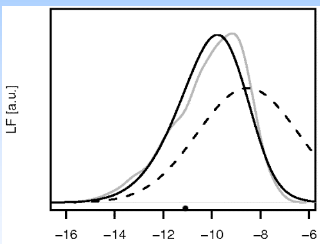
A Closer Look at the Antennae's SC System

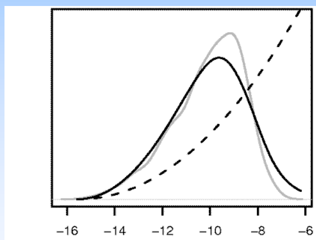
The SC Luminosity Function (LF) has a turnover to 99.5 % significance! * (Anders+07)

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

YSCs = best proxies for MC cores & high SFE regions

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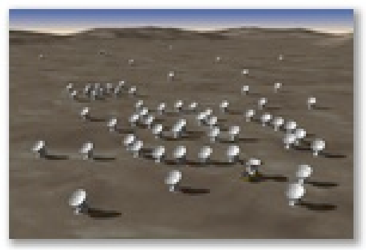
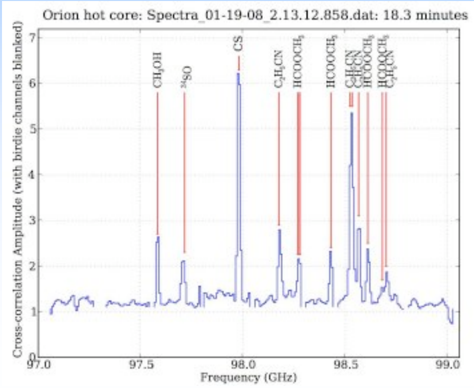
Atacama Large Millimeter Array : ALMA

➜ high sensitivity & high spatial resolution
observations of molecular gas



80 antennas 5000m

Jan.08
1. interfer.
spectrum



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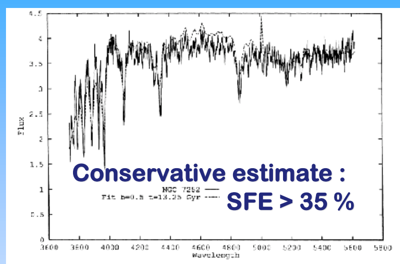
Globular Cluster Formation in Interacting Galaxies & Mergers



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, $Z = (0.5 \ldots 1)\ Z_\odot$,

long-lived : young Globular Clusters

N(young GCs) ~ N(old GCs) ! *

Secondary GCs = eternal tracers of violent SF epoch.

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* Background :

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

Ashman & Zepf (1993) : $<T_{GC}>_E = 2 <T_{GC}>_{Sp}$
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

$<T_{GC}>_E = 2 <T_{GC}>_{Sp}$ (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) $Z \sim (0.5 - 1)\ Z_\odot$

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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

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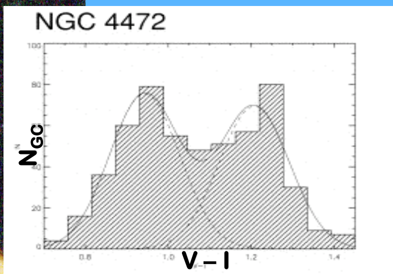
Globular Cluster Analyses

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

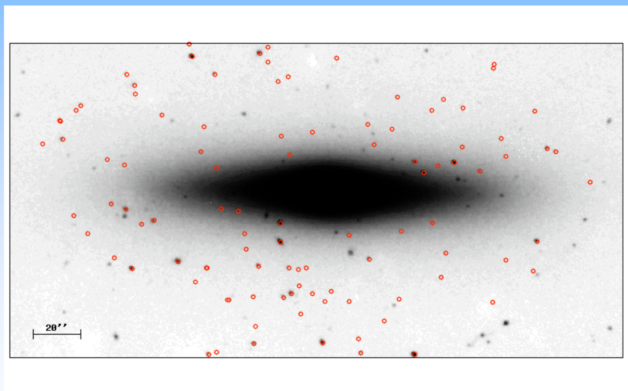
= key tracers of their parent galaxy's (violent) SFH & metal enrichment histories over cosmological lookback times, i.e. back to the very onset of SF in the Early Universe.

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

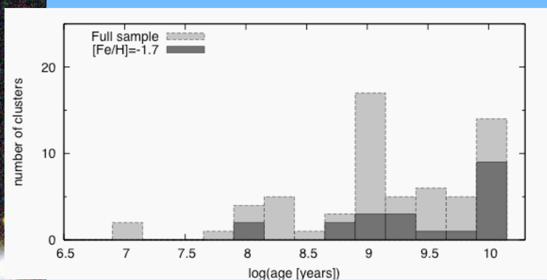
GC population in S0 NGC 4570 : (Kotulla & Fritze 08)



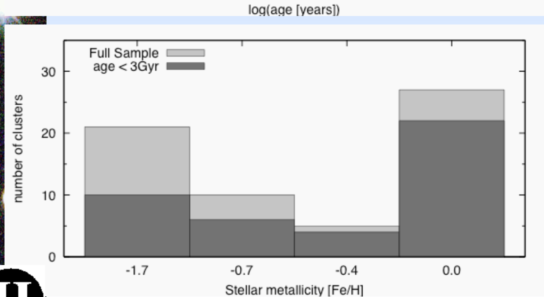
HST ACS g, z (VCS)
+ NTT-SOFI K to 21.3 Vega mag

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

UH