Star formation in interacting and merging galaxies
Outline

1- How much Star Formation is enhanced in interacting/merging galaxies?

2- Quantifying Star formation modes; main sequence, Starburst, mergers?

3- Modes of Quenching: SF and AGN feedback AGN positive feedback in merging galaxies?
1- Impact of interactions on SFR

Very high impact, according to some simulations!

Numerical simulations use recipes, for the sub-grid physics Katz (1992), Mihos & Hernquist (1994, 96)
Schmidt law with threshold, with exponent $n=1.5$

Results depends on disk stability

Without bulge, disk more unstable
At the end, the same SFR
Evidence of dynamical triggering

Interacting galaxies have more SF
Larson & Tinsley (1978)
Colors of interacting galaxies show evidence of recent bursts

ULIRGs are all mergers of galaxies
(e.g. Sanders & Mirabel 1996)

- Interacting galaxies don't show intense starbursts
  (Bergvall et al 03), or only in their centers

Interactions: necessary condition, but not sufficient

Radial gas flows due to bars, or spirals (+DW triggering)
Molecular gas concentrations, and circumnuclear starbursts
(e.g. Sakamoto et al 1999, Buta & Combes 96, Knapen 2004)
Mechanisms

Tidal forces ➔ Spiral and bars: torques ➔ radial gas flows

Interacting galaxies appear to have more H$_2$ content by 4-5
And more concentrated (e.g. Braine & Combes 1993)

The condition of starburst: accumulating gas in a time short enough that feedback mechanisms have no time to regulate

Compressive tidal forces
For a spherical density profile in a power-law $\rho (r) \sim r^{-\alpha}$, then the acceleration is in $r^{1-\alpha}$, so the attraction can increase with distance, if $0 < \alpha < 1$

➔ the tidal force is compressive $F_{\text{tid}} \sim (1-\alpha) r^{-\alpha}$
In particular, for a core density (rotation curve $V$ is in $r^{1-\alpha/2}$)
Interactions: observations

More SSFR in close pairs

5.3 increase in SSFR for low mass
(10^8-10^{11} Mo) and a factor of \sim 2.1
for high mass (10^{11}-10^{13} Mo)

Less in cluster environment

As seen in SDSS pairs by
Ellison et al 2008, Patton et al 2013
Until 150 kpc separation

Also SF triggering by interaction at higher z : 0.1 < z < 0.6
accompanied by asymmetries Patton et al 2005

At z=1.2 (COSMOS) more triggered SF in low-mass galaxies
(Ideue, Taniguchi et al 2012)
Minor mergers are important in global SF

In ETG: 14% if the SFR today
LTG (Sb/Sc) 53%
ETG: SF due to minor mergers
⇒ 24% of SF in LTG is due to minor mergers

Fraction of the cosmic SF induced by minor mergers = 35%

Origin of the bulge and BH growth?

Kaviraj 2014
Star formation at $1.6 < z < 4.8$

CANDELS and GOODS-S, Wiklind et al 2014

The most SF: Interacting galaxies, 28% gas fraction
Influence of minor mergers

Can have a significant Impact on SF Depending on many parameters

Heating of the old stellar disk

Remnant can rebuilt a cold disk, if gas-rich satellite

Cox 2009
Direct orbit merger gSb gSb

Gas flows through bars in galaxy interactions

E0    Sa    Sbc    Sd

GALMER
Di Matteo et al  07

A high trigger
In mergers is rare

<10% SF in z=0.6
major mergers
For Massive Gal
Robaina et al 2009
Gas flows produce starbursts

Retrograde orbits produce more starbursts
Gas flows IN and OUT

direct orbit flyby gSa gSa

100kpc size
Metallicity dilution

Gas flows due to gravity torques during an interaction ➔ Fresh gas, low-Z in the center (also Rupke et al 2010)
Amplitude 0.2-0.3 dex in agreement with observations (Kewley et al. 2006, Rupke et al. 2008)
Dilution due to flybys

Dilution seen in fly-bys also, \textit{Montuori et al 2010}

Duration $< 500$ Myr

$\alpha$ elements enrichment during this phase

$\Rightarrow$ May help to date the event
Enrichment in $\alpha$/Fe, speed of star formation cycles
Fundamental metallicity relation

Requires slow gas infall, chemical time-scale long wrt dynamical

Mannuci et al 2010
Gas-rich galaxies, high resolution

Intermediate mass, 65% of gas

Evolution during 400 Myr Perret, Renaud et al 2014
Influence of interaction/merger

No impact at all
Same SFR for isolated galaxies
Temperature floor?, EoS? Saturation?

Perret, Renaud et al 2014
KS law: Essential role of H2

Bigiel et al 2008
Average over 7 galaxies
Confirmed with 38 galaxies, Heracles, Things
Leroy et al 2013
Disk simulations with H2/Hi

$\alpha_{fb}$ energy fraction for SN feedback

$\chi$ UV radiation field

100 Myr -- $\alpha_{fb}=40\%$

$\chi \times 500$ UV factor

H2 formation enhances the SFR

Then the feedback expels gas

$\Rightarrow$ Thicker gas disk

Halle & Combes 2013
Disk simulations with H2/HI

\[ \alpha_{fb} = 0\%, \ c_* = 0.1 \]

\[ \alpha_{fb} = 0\%, \ c_* = 0.01 \]

\[ \alpha_{fb} = 10\%, \ c_* = 0.1 \]

\[ \alpha_{fb} = 10\%, \ c_* = 0.01 \]

Halle & Combes 2013
2- Star formation modes: main sequence, starburst?

Merger fraction in the EGS
Low and constant: the decrease in SFR in this z-range comes from gas fraction or SF efficiency, but not from the decrease of mergers

Lotz et al 2008

![Diagram showing merger fraction over redshift with data points and error bars.](image)
Merger (major+minor) Fraction from GEMS

< 10% of SF in z=0.6 massive galaxies is triggered by major interactions

Robaina et al 2009

Starburst mode at z=2
Only 10% of the SF

Rodighiero et al 2011
Herschel-GOODS

Jogee et al 2009

→ Compatible with the GALMER simulations

Di Matteo et al 2007
Half of spirals at $z=0.65$ are found in a major merger phase (IMAGES)
MASSIV: 35% of $M^* > 10^{10} M_{\odot}$ have undergone a major merger since $z=1.5$

Lopez-Sanjuan et al 2013
Relative role of gas accretion and mergers

Analysis of results from a cosmological simulation with hydro: most of the SF is due to smooth flows

Dekel et al 2009

Fraction of mass acquired from accretion 77% (mergers 23%) until $z=0$  
Lhuillier et al 2011
Mergers or secular evolution: question of mass

Hierarchical model
Mergers down to 1/20 mass ratios
Success for $M^* > 10^{11} M_\odot$
But not below

→ Secular evolution

8600 galaxies $M > 5 \times 10^{10} M_\odot$, COSMOS $z = 0.2-1$

Oesch et al 2010
Contribution of ULIRGs, LIRGs...

ULIRG are not predominant

From Herschel PEP

Magnelli et al 2013
Main sequence, Major mergers

80 Galaxies, $z=2$  $M^* > 10^{10}$Mo
During mergers, still gas accretion
May be 15% due to mergers?

Kaviraj et al 2013

Wuyts et al 2011

<table>
<thead>
<tr>
<th>Fraction of SF budget</th>
<th>Non-interacting late-types</th>
<th>0.55±0.14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Major merger</td>
<td>0.27±0.08</td>
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<tr>
<td></td>
<td>Spheroids</td>
<td>0.18±0.06</td>
</tr>
</tbody>
</table>
PHIBSS: 52 galaxies

Molecular gas at IRAM, at z~2.3 and at z~1.2

High detection rate >85%, in these « normal » massive Star Forming Galaxies (SFG)

Quiescent SF, in the main sequence

Gas content ~34% and 44% in average at z=1.2 and 2.3 resp.

SFR proportional to $M_*^{0.8} (1+z)^{2.7}$

Tacconi et al 2010, 2013
Evolution of specific SFR

\[ t_{dep} = \frac{1.5}{1+z} \text{ Gyr} \]

Comparison with COLDGASS at \( z = 0 \)

Green: optical surveys
Starbursts $0.2 < z < 1$

Star formation efficiency and gas fraction $sSFR = \frac{SFExMg}{M^*}$

$<z=1>/<z=0>$ 2.1 and 3.8 (with upper limits) 3.2 and 2.5

Both contribute, factor 3+1 increase between $z=0$ and 1

SF efficiency should also be increased due to more violent dynamics

*Combes et al 2013*
3- Modes of Quenching

- **Rapid**: Feedback from SF, from AGN
- **Slow**: Morphological quenching, after bulge formation

T-quench $\sim 2$-4 Gyr

100 Myr

Schawinski 2013
AGN-driven molecular outflows

Mrk 231
AGN and also nuclear Starburst, $10^7$-$10^8$ Mo
Outflow 700 Mo/yr

IRAM Ferruglio et al 2010

Aalto et al 2012
high-density molecular tracers HCN, HCO+, HNC, HC3N CN, …
AGN feedback in mergers

SFR \sim \rho^n \text{ with } n=1, 1.5, 2
SN feedback +
BH growth and associated feedback

Obvious crucial parameter
How much feedback?

\textit{Gabor & Bournaud 2014:}
No quenching effect

Springel et al. (2003-2005),
Hopkins et al. 2006
Feedback in low-luminosity AGN

NGC 1433: Sy 2 barred spiral, the « Lord of the Rings »

The smallest molecular AGN-driven outflow

CO(3-2) with ALMA (Cycle 0)

Beam = 0.5” = 24pc

Flow of 60pc size

Combes et al 13
AGN winds trigger Star Formation?

Cooling efficient (free-free, metals)
Flow unstable, if $R = Prad/Pgas < 0.5$ (Krolik 1981), and
$R \approx 0.07 \frac{M_{BH}}{M_{crit}} f_{EDD} \approx 0.07$

$\Rightarrow$ Multiphase, with RT instabilities

Time-scale for cooling $<< 1$Myr
At kpc scales, $\Rightarrow$ SF induced

The SF results in a Luminosity Comparable to $L_{AGN} \approx 100 M_{\odot}/yr$!

This means that SB or AGN outflows are difficult to disentangle
All could be due to AGN

Zubovas & King 2014
CONCLUSION

- Significant impact of interactions/mergers, trigger starbursts
- Depletion time scale lower in galaxy centers, as at high z
- Stars form essentially on the MS (starbursts 10%)
- Evidence of inflow/outflow: quenching by SN, powerful AGN
- AGN positive feedback, impact in merging galaxies