The evolution of starburst galaxies

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Overview

✦ Taxonomy
  • What is a starburst galaxy?
  • Post-starburst / E+A / K+A galaxies

✦ Selection methods

✦ Recent results
  • Merger simulations
  • Build-up of the red sequence and redshift evolution
  • (post)-starburst - AGN connection
  • Evolution of star formation rate
  • Cluster environment
Why are starburst galaxies important?

✦ What is the dominant mode of star formation in galaxies?
  • Bursty or quiescent?
  • In bulges or in disks?

✦ Does the dominant mode change with $z$?
  • How do galaxy bulges form/grow?
  • Bulges = black holes: relation to galaxy evolution?

✦ Role of mergers in galaxy evolution?
  • How well do galaxies follow Dark Matter’s hierarchical growth?

✦ Physics of high mass star formation
  • Millions of OB stars
  • Outflows and self-regulation
What are starburst galaxies?

✦ Extreme events
  • Convert ~all ISM into stars at ~100% efficiency in ~$10^8$ yrs
  • Scale ~few kpc = circumnuclear (at least in local Universe)

✦ Definition/selection varies:
  • IR bright
    - low-z ULIRGS are extreme examples
  • Birth rate or SFR/M* (specific SFR)
    - time to build stellar mass at current SFR $<< t_H$
  • Intensity (surface brightness)
    - Maximum close to $20 \text{ M}_\odot/\text{yr/kpc}^2$
  • Causality
    - consume all gas in ~one dynamical time

✔ Easy observables
✘ Difficult observables
✔ Better physical motivation
✘ Dependent on mass and redshift
Two problems

1) Not a discrete class

Are the peaks part of a fluctuating disk cycle, or are they once-in-a-lifetime life-changing events?

How do the peaks decay? (....SNe/AGN feedback)

Need to detect starbursts from peak to trough.....

2) Threshold detection

SDSS DR7 Starforming galaxies

De Lucia & Blaizot semi-analytic SFH (Pacifici et al. 2011)
Building stellar populations

~starburst galaxy

~~post-starburst galaxy~~

~elliptical galaxy~~

<table>
<thead>
<tr>
<th>~starburst galaxy</th>
<th>Main Sequence Lifetime</th>
<th>Spectral features</th>
</tr>
</thead>
<tbody>
<tr>
<td>O5</td>
<td>~10^6</td>
<td>Steep UV continuum He absorption</td>
</tr>
<tr>
<td>B3</td>
<td>~10^7</td>
<td>Some Balmer (HI) absorption</td>
</tr>
<tr>
<td>B8</td>
<td></td>
<td>Strong UV continuum excites nebular emission lines</td>
</tr>
<tr>
<td>A0</td>
<td>~5x10^8</td>
<td>Strong Balmer lines and Balmer break Ca H&amp;K lines</td>
</tr>
<tr>
<td>A7</td>
<td></td>
<td>A trend with temperature within A stars: T↓ Ca↑ break ↓</td>
</tr>
<tr>
<td>F0</td>
<td>~8x10^9</td>
<td>Strong metal lines Balmer series weak</td>
</tr>
<tr>
<td>F8</td>
<td></td>
<td>Strong 4000Å break</td>
</tr>
<tr>
<td>G5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Galaxy spectrum = stellar spectra+IMF+SFH+ZH (x dust)
  - Invert to recover SFH
  - Light from some galaxies can be dominated by one type of star

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Post-starburst spectra

“colour is typical of Sb spirals .... but the integrated spectrum of an Sb spiral is completely incompatible with the spectra of the 3 objects”

“...consistent with an old population mixed with an equal blue luminosity of A-stars, which indicates a large burst of star formation $10^9$ years before the light left the galaxy”
Post-starburst spectra

“compare with simulations to show that the galaxies are consistent with being the descendants of gas-rich major mergers”

“post-starburst galaxies could account for ~40% of the growth rate of the red sequence”

Wild et al. 2009
"Similar to other massive galaxies at $z \sim 2$ the galaxy is compact, with an effective radius of $2.1 \pm 0.3$ kpc"

"the data can be fit with an extreme burst of $\sim 5000$ M$\odot$/yr at $z \sim 2.2$ (blue), or with a star formation rate of $\sim 500$ M$\odot$/yr sustained over $\sim 1$ Gyr (orange)"
**Post-starburst selection - traditional**

**Problems:**

- EQW emission/absorption combination = complicated physical selection function
- Ignores possibility for slow decay in SFR after starburst
- Impossible to study evolution of starburst -> post-starburst

**Additional problems with this selection:**

- excludes objects with AGN
  - and post-starbursts have higher probability of having an AGN (Wild et al. 2007, Yan et al. 2009)
Selection with PCA

- Parameterise shape of spectrum using spectral indices
- Plot distribution of indices for a complete sample of galaxies
- New definition of starburst galaxy: OB stars dominate spectrum
  - Purely practical (allows us to track starbursts -> post-starbursts)

Stronger Balmer lines

Increasing 4000A break (decreasing SSFR)

SDSS DR7 galaxies
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Reminder:

- Stronger Balmer lines
- Increasing 4000Å break (decreasing SSFR)

SDSS DR7 galaxies

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(Post-) starburst images

~10 Myr

~600 Myr
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(Post-) starbursts in merger simulations

✧ ~70 Smoothed Particle Hydrodynamic (SPH) simulations of galaxy mergers

• Johansson, Naab, Burkert 2009
• Gas fraction 20, 40, 80%
• With and without QSO feedback
• Major and Minor mergers (1:1, 1:3)
• Different orbits

✧ Star formation history -> spectra

• Bruzual & Charlot spectral synthesis models
• + Balmer emission lines + dust
• see also Patrik Jonsson et al. and the Sunrise code

(Post-) starbursts in merger simulations

- Conclusion 1: Gas rich spiral merger leads to remnants with strong Balmer absorption, before galaxy enters red sequence
- Conclusion 2: “AGN feedback” makes little difference to spectral signature
  - Decay in SF caused by gas exhaustion + SNe feedback
- For VVDS dataset (low R, low S/N):
  - Decay timescale must be short: < 1e8 years
  - Detectable burst age 0.6Gyr for strongest burst
  - Detectable burst mass fraction >~5-10%
  - i.e. extreme post-starbursts

Build-up of the red-sequence

**Vimos VLT deep survey (VVDS)**
- Le Fèvre et al. 2004 etc.
- $I_{AB} < 24.5$
- No colour pre-selection
- Spectral resolution R~230
- Field sample (i.e. not cluster)

**This work:**
- $0.5 < z < 1.0$
- $I_{AB} < 23.0$
- 1246 galaxy spectra
- SN/pixel > 6.5

Build-up of the red-sequence

- 16 Balmer strong galaxies with $M^* > 6 \times 10^9 \ M_\odot$
- 5 have no residual star formation
  - Heading for the red sequence?
  - Typical red sequence stellar masses

Build-up of the red-sequence

Total mass flux through post-starbursts onto red sequence (for 5 with no ongoing SF):

\[
\dot{\rho}_{B \rightarrow R,PSB} = \frac{M_{B \rightarrow R,PSB}}{\text{Vol} \times t_{PSB}} = 0.0038 \text{ M}_\odot/\text{Mpc}^3/\text{yr}
\]

Fraction of red sequence accounted for by post-starburst galaxies (compared to Arnouts et al. 2007):

\[
\frac{\dot{\rho}_{B \rightarrow R,PSB}}{\dot{\rho}_{B \rightarrow R}} = 38^{+4}_{-11}\%
\]

**Starburst-AGN connection**

Stellar continuum -> age of the starburst

Emission lines -> black hole accretion (+ instantaneous SFR)

- 400 strongest starburst to post-starburst bulge-galaxies in local Universe
  - $0.01 < z < 0.07$ (3” SDSS fibre $\Rightarrow$ 0.6 - 4 kpc diameter)
  - Stellar surface mass density $> 3 \times 10^8 \, M_\odot/kpc^2$ (where majority of $L[\text{OIII}]_{\text{AGN}}$ originates)
  - **Complete sample** to 600Myr: constant number per unit starburst age
  - Starburst stellar mass fractions $\sim$10-20% (continuum fits and $\text{Ha}$ luminosities agree)

Wild et al. 2010a, MNRAS
Completeness

- [OIII] -> bolometric luminosity of AGN
  - correlates with numerous direct measures of $L_{bol}$ (Mulchaey et al. 1994)
  - correlates with (compton thin) $L_{X-ray}$ for obscured AGN (Heckman et al. 2005)
  - too far from nucleus to be badly effected by dust obscuration
- Strong starbursts mask weak AGN - we allow for this in our calculations

Wild et al. 2010a, MNRAS
Histograms are corrected for incompleteness in the AGN sample, bins >50% complete are plotted

- Starbursts have more high accretion and high growth-rate AGN episodes compared to ordinary starforming bulges
  - Enhancement less pronounced in the youngest starbursts

Wild et al. 2010a, MNRAS
Timing the AGN accretion

- First 200Myr dominated by **fast** ejecta from high mass stars (SNe,O/B)

- After 50Myr first appearance of **slow** stellar ejecta from low-mass stars

- Mass loss rate from stars in starburst $\tau_{\text{exp}} = 0.3\text{Gyr}$

- Black Hole starts to accrete after $\sim 200\text{Myr}$.

- Consistent with M-\(\sigma\) relation after $\sim 10\text{Gyr}$

- Accretion commences when fast ejecta have decayed

  - Feedback from fast stellar ejecta prevents accretion??

- Accretion efficiency: $\sim 1\%$ of low mass stellar ejecta

  - (see also Ciotti & Ostriker 07; Kauffmann & Heckman 09)

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Post-starburst AGN connection

✧ Method:
  • Stellar continuum: complete sample of starburst -> post-starburst galaxies
  • Nebular emission lines: black hole accretion rate

✧ Results:
  • Delay between onset of starburst and black hole accretion
  • Too long for simple stellar ejecta hypothesis
  • Too long for dynamical (BH merger) predictions

✧ Conclusion??:
  • Black holes grow through accretion of slow stellar ejecta
  • Feedback from SNe prevents accretion early on
Decline of SFR in starbursts

ентр 3 phases:

- Peak ~ 50 Myr
- Slow decline ~ 350 Myr
- Rapid decline into late post-starburst phase

~0.3Gyr decline in agreement with:

✦ Gas consumption times from Kennicutt-Schmidt relation (Kennicutt 1998)
✦ Resolved stellar populations of local dwarfs (McQuinn et al. 2010)
✦ Starbursts in close-pairs (Barton et al. 2000; Freedman Woods et al. 2010)
✦ Stellar surface mass densities of elliptical galaxies (Hopkins & Hernquist 2010)
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Galaxy populations in clusters

- Decrease in average SF with decreasing distance from centre of cluster
  - Caused by decrease in number of star forming galaxies
  - For galaxies with same recent star-formation (1Gyr), no strong change in instantaneous SFR

von der Linden, Wild et al. 2010
Cluster galaxies die slowly

- Post-starburst galaxies have environments similar to star-forming galaxies
- Only tentative evidence of tiny enhancement in PSBs at centre
  - Expect some: we see ram-pressure stripping in some clusters, but can’t be dominant
Why are (post-)starburst galaxies interesting?

✧ Build up of red sequence:
  • Gas-rich major-merger + starburst could account for 40% of growth of red-sequence at z~0.7

✧ Post-starburst - AGN connection:
  • Enhanced AGN activity in all starbursts
  • More enhanced in older starbursts

✧ Evolution of star formation following starburst:
  • Star formation decays slowly, timescales of ~300-400Myr

✧ Cluster galaxies die slowly:
  • Slow transition from star forming to quiescent galaxies
  • No evidence for enhanced post-starburst population
Work in progress

✧ IRAM-30m CO data
  • Evolution of cold gas mass in starbursts
    - With Nicole Nesvadba and Matt Lehnert

✧ Herschel 5-band FIR photometry
  • Evolution of dust-to-gas ratio and dust temperature
    - With Elisabete da Cunha and Angela Mortier

✧ Combining spectroscopic + morphological info
  • Both give timescales -> both should agree?
    - With Jakob Walcher, Peter Johansson