Starburst galaxies at low and high redshift

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Starburst galaxies at low and high redshift

Credits

- **starbursts at low redshift**
  - Leonie Snijders (see poster)
  - Frank Israel
  - Natascha Förster Schreiber
  - Sabine Mengel
  - Alan Moorwood (ESO)
  - Tino Oliva (Arcetri)
  - Karín Menéndez-Delmestre
  - Maaike Damen
  - Inti Pelupessy
  - Rowin Meijerink (see poster)

- **starbursts at high redshift**
  - Kirsten Kraiberg Knudsen (PhD October 2004)
  - Tracy Webb
  - Lottie van Starkenburg
  - Marijn Franx
  - Pieter van Dokkum (Yale)
  - Ivo Labbé
  - Greg Rudnick (MPA)
  - Hans-Walter Rix (MPIA)
  - Mariska Kriek
  - Arjen van der Wel
  - Stijn Wuyts
  - Andrew Blain (Caltech)
  - Jean-Paul Kneib (Toulouse)
Some starburst researchers in Leiden

Starburst galaxies at low and high redshift
« The stellar systems are scattered through space as far as telescopes can penetrate. We find them smaller and fainter, in constantly increasing numbers, and we know that we are reaching out into space, until, with the faintest nebulae than can be detected with greatest telescopes, we arrive at the frontiers of the known Universe. »

*Edwin Hubble, The Realm of the Nebulae (1936)*
A starburst galaxy is a galaxy with such a high star formation rate that it will turn all of its gas into stars in $t_b \ll t_{\text{Hubble}}$.

**Milky Way:**

$M_{\text{H}_2} \approx 2.5 \times 10^9 \, M_\odot$

$\dot{M} \approx 1 \, M_\odot \, \text{yr}^{-1}$

$\Rightarrow t_b \approx 2 \cdot 2 \cdot \frac{M_{\text{H}_2}}{\dot{M}} \approx 10^{10} \, \text{yrs}$

correction factor for mass return from stars

$M_{\text{H}_2} \approx 0.5 \, M_{\text{gas}}$

$\Rightarrow$ gradual buildup of disk
The nearest starburst galaxy: M82

\[ L_{\text{FIR}} \approx 3.1 \cdot 10^{10} L_\odot \]
\[ \dot{M} \approx 3 M_\odot \text{yr}^{-1} \]
M82 integrated spectra

A–star population
0.1 – 1.0 Gyr
unobscured "post-starburst" population

< 20 Myr
more obscured recent starburst

[OII] : 3727 Å, Hα : 6563 Å
Starbursts are (usually) dusty

Starburst galaxies at low and high redshift
A luminous infrared galaxy: the Antennae

- Crossing orbits give gas concentration in interaction zone
- Intense obscured star formation in overlap region
- Most intense star formation is obscured

\[ \frac{L_{\text{FIR}}}{L} = 3 \times 10^{11} \]
\[ \dot{M} = 30 M_{\odot} \text{yr}^{-1} \]

(Snijders & Van der Werf, in preparation)
Starbursts and galaxy evolution

During a starburst, galaxies evolve strongly in:

- colour
- gas content
- morphology
- bolometric luminosity

This evolution is rapid: on a dynamical (merging, crossing) timescale, i.e., $t_b \sim 10^8$ yrs

$\Rightarrow$ starbursts are a key process in galaxy evolution
An ultraluminous infrared galaxy: Arp220

\[ L_{\text{FIR}} \equiv 1.5 \cdot 10^{12} L_{\odot} \]

\[ \dot{M} \equiv 150 M_{\odot} \text{ yr}^{-1} \]
Starburst galaxies at low and high redshift

Starformation in ULIGs

Arp220: $M_{H_2} \sim 1.6 \cdot 10^{10} M_\odot$
$\dot{M} \sim 150 M_\odot \text{ yr}^{-1}$
$\Rightarrow t_b \sim 2 \cdot \frac{M_{H_2}}{\dot{M}} \sim 2 \cdot 10^8 \text{ yrs}$

correction factor for mass return from stars

NB: $t_b \sim \text{few} \ 10^8 \text{ yrs} \sim \text{merger timescale}$
$\sim \text{dynamical timescale}$
$\sim \text{(crossing/rotation time)}$
$\sim \text{free-fall time protogalaxy?}$

Such high SFRs can build up an entire galaxy in $t \ll t_{\text{Hubble}}$
$\Rightarrow \text{relation to galaxy formation?}$
Simple-minded estimate of "maximum star formation rate"

In the absence of external pressure, the maximum star formation rate occurs when a gas mass is turned into stars on the free-fall timescale.

\[ \dot{M}_{\text{max}} = \frac{M_{\text{gas}}}{t_{\text{ff}}} = M_{\text{gas}} \sqrt{G \rho} \]

Self-gravitating sphere: \( R^2 = \frac{3}{4} \frac{\sigma^2}{\pi G \rho} \)

\[ \dot{M}_{\text{max}} \approx 100 \left( \frac{\sigma}{100 \text{ km/s}} \right)^3 M_\odot \text{ yr}^{-1} \]

Initial starburst – rapid formation of bulk of the stellar population

⇒ formation of spheroids?

Implication: high SFRs are found in the most massive galaxies
Do "maximum starburst" galaxies exist?

\[
\frac{L_{\text{bol}}}{L_{\odot}} \geq A \cdot 10^{10} \frac{\dot{M}}{M_{\odot} \text{ yr}^{-1}}
\]

\[\Rightarrow \ \text{ULIGs} \ (L_{\text{bol}} > 10^{12} L_{\odot}) \text{ have } \dot{M} \geq \dot{M}_{\text{max}}!\]

\[A = f(\text{IMF parameters}) \geq 1\]

At \( L > 10^{12} L_{\odot} \) is \( \frac{L_{\text{FIR}}}{L_{\text{bol}}} \geq 90\%
\]

(cf., 30–50% for normal spirals)

ULIGs are "maximum starbursts"
Starburst galaxies at low and high redshift

- Starbursts cannot be simply scaled up.
- More intense starbursts are also more efficient with their fuel.

\[ \frac{L_{\text{IR}}}{L_{\text{CO}}} \propto \frac{\text{SFR}}{M_{\text{H}_2}} \]

ULIGs: \( \left\langle \frac{L_{\text{FIR}}}{M_{\text{H}_2}} \right\rangle \geq 39L_\odot M_\odot^{-1} \)

Milky Way: \( 4L_\odot M_\odot^{-1} \)

Galactic GMCs: \( 7L_\odot M_\odot^{-1} \)

Orion: \( 40L_\odot M_\odot^{-1} \)

\( L_{\text{IR}} \propto \text{SFR} \)
Role of dense gas

$L_{\text{IR}}/L_{\text{CO}} \propto \text{SFR}/M_{\text{H}_2} \propto \text{SFE}$

$L_{\text{HCN}}/L_{\text{CO}} \propto \text{mass fraction of dense gas}$

- More dense gas means more efficient star formation.

(Gao & Solomon 2001)
ULIGs and galaxy formation

- Locally, ULIGs are energetically unimportant: contribute only 2% of local bolometric energy density.

How important are ULIGs at high z?

⇒ observe redshifted far-IR emission in submillimetre with JCMT/SCUBA.

- Local ULIGs are NOT forming galaxies: there is a massive pre-existing population.

How is this for high-z ULIGs? Measure rest-frame K-band magnitudes

⇒ observe redshifted K-band emission in mid-IR with Spitzer Space Telescope.
Intermediate redshift: $z = 0.5–1.5$

At 15 μm, the PAH complex at restframe 6–8 μm is picked up at $z \sim 1$.

Spectroscopy shows that these are substantial starburst galaxies (Rigopoulou, Franceschini, Van der Werf 2000)

deep ISOCAM 15 μm (colours) and 7 μm (contours) imaging of HDF-S (Oliver et al 2002)
Starburst galaxies at low and high redshift

The nature of the mid-infrared population

Figure 12: Flores et al. 1999

Rest-frame B-band

[O II] H δ H ε

Old starburst

(Flores et al. 1999)

Rest-frame R-band

H α [NII]

Young, active starburst

(Rigopoulou et al. 2000)
Photometry: massive stellar population

- Balmer break reveals prominent evolved population

- Spectral energy distribution gives baryonic mass to factor of ~2: $2.3 \cdot 10^{11} M_\odot$: massive

- SFR $\sim 50 M_\odot$ yr$^{-1}$

(Franceschini, Rigopoulou, Van der Werf et al. 2003)
Spectroscopy: high dynamical masses

- $z = 0.58$ spiral galaxy
- Prominent flat rotation curve
- $v_{\text{rot}} = 415$ km/s
- 40 kpc diameter disk
- Implied mass $10^{12} M_\odot$

(Rigopoulou, Franceschini, Thatte, Van der Werf et al. 2002)
Massive galaxies at $z \sim 0.6$

IR-luminous galaxies have high $L/M$ and high $M$!
Cosmic energy density

- Microwave Background
- IR/Optical Background
- X-Ray Background
- Big Bang
- Stars+BlackHoles
- AGN

Is obscured star formation important?

- **Direct starlight:**
  \[ vI_v = 1.7 \times 10^{-5} \text{ erg/s/cm}^2/\text{sr} \]

- **Far-IR background:**
  \[ vI_v = 3.1 \times 10^{-5} \text{ erg/s/cm}^2/\text{sr} \]

Obscured star formation dominates.
SCUBA/JCMT cosmological survey

- 12 gravitationally lensing clusters
- 1 blank field (NTT Deep Field)
- Survey area 72 arcmin$^2$
- Deepest fields are confusion-limited (2 mJy)
- 55 sources detected at 850 µm

Knudsen PhD thesis
Van der Werf
Kneib
Submillimetre cosmology

Large negative $k$-correction:

- Submm samples have high proportion of high-$z$ galaxies
- Galaxies up to $z \sim 10$ detectable
- Brightness-limited $\sim$ volume-limited
- Luminosities without precise redshifts
- Sources do not fade much from $z=1$ to 10
- Deeper surveys probe fainter galaxies, not higher $z$
Counts and backgrounds

Resolved background at 850 μm:

~25% down to 2 mJy

Submm background comes from small number of (ultra)luminous galaxies
Submillimetre source counts

- Counts imply strong evolution
- First time the faint submm population is substantially probed
- Connection with optical population

(Knudsen, Van der Werf & Kneib 2004)
luminosity evolution:

$L_\star \propto (1+z)^p$

density evolution:

$N \propto (1+z)^q$

Counts + background imply pure luminosity evolution proportional to $(1+z)^3$
The Cosmic Star Formation History

Starburst galaxies at low and high redshift
In the high-\(z\) universe, a much higher fraction of star formation is obscured than at \(z = 0\).
ULIGs from UV to IR

Compact core: 80% of mid-IR
<7% in far-UV

Arp 220

Surace et al. (2001); Soifer et al. (2000);
Submm galaxies in the NTT Deep Field

Not an ERO (?)

ERO

(Knudsen et al. in preparation)
Rest-frame SEDs: Lyman break galaxies

![Graph showing rest-frame SEDs for Lyman break galaxies with annotations for HDF-S and MS1054-03]
Rest-frame SEDs: distant red galaxies
Selection of distant red galaxies

Simple photometric criterion:

\[(J_s - K_s)_J > 2.3\]
Submm galaxies and DRGs

- Lyman Break Galaxies have no detectable submm emission even after massive source stacking.
- Distant Red Galaxies are massive and have high SFRs.
- DRGs: $3 \text{ arcmin}^{-2}$ for $K<22.5$ same source density as submm galaxies with $>0.8 \text{ mJy at 850 } \mu\text{m}$
- 1 FIRES field observed with SCUBA: 1 DRG detected (5 mJy)
- connection between sub-mJy submm galaxies and DRGs?
Breaking the confusion barrier: gravitational lenses

A2218

Starburst galaxies at low and high redshift
A2218: SCUBA 850 µm
The submm triple behind A2218

Triple image, $z=2.515$

Magnification in total factor 40

Intrinsic 850 $\mu$m flux: 0.9 mJy

Redshifted H$\alpha$: strong star formation

$J-K=2.7$: Distant Red Galaxy

(Kneib, Van der Werf, Knudsen 2004)
Detected both at Owens Valley and Plateau de Bure

CO line width 540 km s\(^{-1}\) \(\Rightarrow\) massive
Conclusions and outlook

- Starbursts are a key process in galaxy evolution
- We are looking towards a strongly obscured universe, energetically dominated by dusty starbursts
- Luminous starbursts tend to have both high $L/M$ and high $M$
- DRGs are massive and have high SFRs; as a population they are at least as important as LBGs for cosmic mass budget and SFR
- Tentative evidence for connection between DRGs and mJy submm galaxies
- The future: SCUBA2, ALMA, JWST, ELT
« We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary, the utmost limits of our Telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial.

The search will continue. Not until the empirical resources are exhausted, need we pass on the dreamy realms of speculation. »

*Edwin Hubble, The Realm of the Nebulae (1936)*