The Peak Epoch of Star Formation Activity

Karina Caputi

Star Formation in Galaxies through Cosmic Times
NOVA PhD Fall School
1-5 October 2012
The Evolution of the Star Formation Rate Density

Hopkins & Beacom (2006)
In perspective...

Until only ~15 years ago, we had quite a sparse knowledge of galaxies at $z>1.5$. The connection between different galaxy populations was unclear.

New facilities ($HST, Spitzer, ground-based 8m-diam. telescopes$) allowed us to create a more complete and clearer picture of the Universe at high $z$. 
The highest $z$ known galaxy over the last decades

<table>
<thead>
<tr>
<th>Date</th>
<th>Galaxy</th>
<th>$z$</th>
<th>Search Technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999...</td>
<td>SSA 22-HCM1</td>
<td>5.74</td>
<td>Narrowband imaging</td>
<td>1</td>
</tr>
<tr>
<td>1998 Oct...</td>
<td>HDF 4-473.0</td>
<td>5.60</td>
<td>Photometric selection</td>
<td>2</td>
</tr>
<tr>
<td>1998 May...</td>
<td>0140+326 RD1</td>
<td>5.34</td>
<td>Serendipity</td>
<td>3</td>
</tr>
<tr>
<td>1997...</td>
<td>Cl 1358+62, G1/G2 arcs</td>
<td>4.92</td>
<td>Serendipity/gravitational lensing</td>
<td>4</td>
</tr>
<tr>
<td>1996...</td>
<td>BR 1202-0725</td>
<td>4.695</td>
<td>Narrowband imaging</td>
<td>5</td>
</tr>
<tr>
<td>1994...</td>
<td>8C 1435+63</td>
<td>4.26</td>
<td>Radio selection</td>
<td>6</td>
</tr>
<tr>
<td>1990...</td>
<td>4C 41.17</td>
<td>3.80</td>
<td>Radio selection</td>
<td>7</td>
</tr>
<tr>
<td>1988...</td>
<td>B2 0902+34</td>
<td>3.39</td>
<td>Radio selection</td>
<td>8</td>
</tr>
<tr>
<td>1985...</td>
<td>PHS 1614+051 companion</td>
<td>3.215</td>
<td>Narrowband imaging</td>
<td>9</td>
</tr>
<tr>
<td>1984...</td>
<td>3C 256</td>
<td>1.82</td>
<td>Radio selection</td>
<td>10</td>
</tr>
<tr>
<td>1983...</td>
<td>3C 324</td>
<td>1.206</td>
<td>Radio selection</td>
<td>11</td>
</tr>
<tr>
<td>1982...</td>
<td>3C 368</td>
<td>1.131</td>
<td>Radio selection</td>
<td>12</td>
</tr>
<tr>
<td>1979...</td>
<td>3C 6.1</td>
<td>0.840</td>
<td>Radio selection</td>
<td>13</td>
</tr>
<tr>
<td>1976...</td>
<td>3C 318</td>
<td>0.752</td>
<td>Radio selection</td>
<td>14</td>
</tr>
<tr>
<td>1975...</td>
<td>3C 411</td>
<td>0.469</td>
<td>Radio selection</td>
<td>15</td>
</tr>
<tr>
<td>1960...</td>
<td>3C 295</td>
<td>0.461</td>
<td>Radio selection</td>
<td>16</td>
</tr>
<tr>
<td>1956...</td>
<td>Cl 0855+0321</td>
<td>0.20</td>
<td>Cluster selection</td>
<td>17</td>
</tr>
</tbody>
</table>
Selection of SF galaxies at z~2-3

Lyman-break selection technique

Introduced by Steidel et al. (1996) to select star-forming galaxies at z~3

Note: low-z contaminants can be 20-30% of sample

Picture Credit: http://www.astro.ku.dk/~jfynbo/LBG.html
Selection of SF galaxies at $z\sim2-3$

[Diagram: Two-color $(U_n-G)$ vs. $(G-R)$ diagram from one of the UV-selected survey fields, demonstrating the UV-selection technique described in Section 2.2. The green and yellow shaded regions mark the $z\sim3$ LBG color selection windows, while the cyan and magenta regions are used to select galaxies at $z\sim2.0$ and $z\sim1.5-2.0$, respectively.]

Picture Credit: Shapley (2011), based on Steidel et al. (2004)
Selection of SF galaxies at z~4-5

changing the set of filters, the technique can be extended to select higher-z galaxies

Caveat of this technique: biased against dusty galaxies!
The proof of success

stacked spectra of ~800 Lyman-break-selected galaxies

Shapley et al. (2003)
Ly-break galaxies vs. Ly-alpha emitters

Lyman-break galaxies are not necessarily Lyman-alpha emitters

The Lyman-alpha line profile depends on the ability of Lya photons to escape dusty/clumpy interstellar medium

**problem:** resonant scattering of photons with HI

**note:** if Lya EW > 100 Å, then age < 50 Myr

*Pictures Credit: Verhamme et al. (2008); see also Neufeld (1990)*
for many years, the search of $z>1.5$ galaxies has been performed on optical images

but the advent of near-IR surveys showed that optical surveys miss a significant fraction of high-$z$ galaxies

Why?
Optical vs Near-IR Galaxy Surveys

for many years, the search of $z > 1.5$ galaxies has been performed on optical images

but the advent of near-IR surveys showed that optical surveys miss a significant fraction of high-$z$ galaxies

Why?

Picture Credit: http://ned.ipac.caltech.edu/level5/Sept01/Malkan/Malkan2.html
Extremely Red Galaxies (ERGs)

defined as galaxies with (i-K) > 4 or (R-K) > 5 (Vega)

*colour selection implies that almost all are at z>1*

(see e.g. Caputi et al. 2004)

![Graph showing spectral energy distribution and colors (I, J, K filters)]

**Problem:** age/dust degeneracy

*Old galaxy or dusty starburst?*

*Picture Credit: Pozzetti & Mannucci (2000)*
Distant Red Galaxies (DRGs)

defined as galaxies with (J-K) > 2.3 (Vega)
(Franx et al. 2003)

selects massive galaxies at z>2

most of them are dusty SF galaxies

Note: at low z -- most massive galaxies are ‘red and dead’

At high z most massive galaxies are actively forming stars!
The BzK selection

selects galaxies at $1.4 < z < 2.5$ -- separates SF and passive

Daddi et al. (2004)
The galaxy stellar mass function to $z \sim 2$

Fontana et al. (2006)
The galaxy stellar mass function at $z>3$

Caputi et al. (2011)
The evolution of the stellar mass density

\[ \log_{10}\left( \frac{\rho_M}{M_{\odot} \text{Mpc}^{-3}} \right) \]

Caputi et al. (2011)
Spectra of z~2-3 galaxies

Maiolino et al. (2008)
The evolution of the $M_{\text{st}}$-Z relation

Maiolino et al. (2008)
Integral field spectroscopy of $z\sim 2$ galaxies

Genzel et al. (2006)
The realm of infrared galaxies

Most of the star formation activity of the Universe at $1 < z < 3-4$ was obscured by dust.

The systematic study of the IR Universe at high $z$ started to be possible with Spitzer and Herschel space telescopes.

IR astronomy is making rapid progress!
The extragalactic IR background

Dole et al. (2006)
A bit of history...

~20 years ago, only a few cases of dusty high-z galaxies known (Rowan-Robinson et al. 1991; Dey et al. 1995)

Radio galaxies were the highest-z known galaxies because relatively dust-free

The first known cases were very powerful sources

AGN quite secure -- but also SF?

Credit: http://www.astr.ua.edu/keel/agn/
A new window to high-z: sub-mm sources

SCUBA on JCMT has enabled first blank-field surveys at sub-mm wavelengths

takes advantage of atmospheric transmission windows

~850 microns

~350 microns

Credit: Hughes et al. (1998)
The negative k corrections

![Graph showing the negative k corrections with wavelength in mm on the x-axis and flux density in mJy on the y-axis. Different curves represent different redshifts (z) from 0.1 to 8.0.](http://www.mpia-hd.mpg.de/homes/decarli/science.html)
Sub-/mm sources are HyperLIRGs

Sub-/millimetre galaxies are powerful, dust-obscured star-forming galaxies (SFR ~ 500 - 1000 M$_\text{sun}$/yr!)

Mostly at $2<z<4$, but some $z>4$ candidates confirmed

Radio is most secured identification method, but also mid-IR detections

Michalowski et al. (2012)
Spitzer / MIPS sources have filled the gap between low-z IR galaxies discovered with ISO, and the rare population of sub-mm galaxies at high $z$.

Spitzer 24 microns / SpUDS Legacy Survey
The evolution of the IR luminosity function

[Graph showing the IR luminosity functions for star-forming galaxies at different redshifts (z~0, z~2, z~1).]

Caputi et al. (2007)
The IR luminosity density associated with SF

Caputi et al. (2007)
The ‘main star formation sequence’ (for galaxies)

Note: the lack of galaxies below the ‘main sequence’ is mainly a selection effect.
The big puzzle: star formation or AGN?

both SF and black-hole activity can produce IR emission

AGN are expected at some point in all massive galaxies at $z \sim 1-3$

but observational evidence of coeval SF/AGN is relatively rare

Bertoldi et al. (2003)
Gas reservoirs in ULIRGs

[Tacconi et al. (2006)]