Optically faint luminous infrared galaxies at z~2: the progenitors of today’s old massive galaxies

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Collaborators: Dey, Jannuzi, Brown, Soifer, Desai, …
Introduction - I: color-magnitude diagrams

- Massive galaxies are red.

Brand et al. in prep
Brown et al. 2006
• Cosmic Downsizing:
  The sites of active star formation shift from high-mass galaxies at early times to lower mass systems at later epochs.

→ Today’s massive “red and dead” galaxies were assembled at high redshifts

Bundy et al. 2006
Introduction - III

- ULIRGs become increasingly important at high z

Candidates for massive galaxies undergoing an intense but dusty and obscured phase of SF and SMBH growth at high z.

Total IR energy density
Low lum galaxies ($L_{\text{IR}}<10^{11}L_\odot$)
LIRGs ($L_{\text{IR}}>10^{11}L_\odot$)
ULIRGs ($L_{\text{IR}}>10^{12}L_\odot$)

Le Floc’h et al. 2005
NOAO Deep Wide-Field Survey

Bootes field - 9.4 deg²

Bw, R, I, K ~ 27.1, 26.1, 25.4, 19.0 mag (Vega).

PIs: A. Dey, B. Jannuzi

Clustering of red galaxies - see talk by M. Brown
Multi-wavelength Observations of the Bootes Field

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Band</th>
<th>Field of View</th>
<th>Sensitivity</th>
<th>Completeness</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLA P-band</td>
<td>90 cm</td>
<td>7 sq.deg.</td>
<td>100µJy</td>
<td>100% complete; van Breugel, PI</td>
</tr>
<tr>
<td>VLA L-band</td>
<td>21 cm</td>
<td>1 sq.deg.</td>
<td>15µJy</td>
<td>100% complete; Higdon, PI</td>
</tr>
<tr>
<td>VLA (FIRST)</td>
<td>21 cm</td>
<td>9 sq.deg.</td>
<td>1mJy</td>
<td>100% complete; public</td>
</tr>
<tr>
<td>Westerbork</td>
<td>21 cm</td>
<td>7 sq.deg.</td>
<td>8µJy</td>
<td>100% complete; Rottgering, PI</td>
</tr>
<tr>
<td>Spitzer/MIPS</td>
<td>24,70,160µm</td>
<td>9 sq.deg.</td>
<td>3.0, 30, 100mJy</td>
<td>100% complete; Jan 2004 GTO</td>
</tr>
<tr>
<td>Spitzer/IRAC</td>
<td>3.6,4.5,5.8,8µm</td>
<td>9 sq.deg.</td>
<td>6.4, 8.8, 51, 50µJy</td>
<td>100% complete; Eisenhardt et al.</td>
</tr>
<tr>
<td>NOAO</td>
<td>J, Ks</td>
<td>5 sq.deg.</td>
<td>23 mag</td>
<td>100% complete; Elston et al. (2005)</td>
</tr>
<tr>
<td>NOAO</td>
<td>K, Ks</td>
<td>9 sq.deg.</td>
<td>19.2 mag</td>
<td>100% complete</td>
</tr>
<tr>
<td>NOAO</td>
<td>J, H</td>
<td>9 sq.deg.</td>
<td>21 mag</td>
<td>40% complete</td>
</tr>
<tr>
<td>NOAO</td>
<td>B_W, R, I</td>
<td>9 sq.deg.</td>
<td>25.5-26.6 mag</td>
<td>100% complete</td>
</tr>
<tr>
<td>NOAO</td>
<td>U</td>
<td>9 sq.deg.</td>
<td>25 AB mag</td>
<td>100% complete</td>
</tr>
<tr>
<td>NOAO</td>
<td>U</td>
<td>1 sq.deg.</td>
<td>26 AB mag</td>
<td>100% complete</td>
</tr>
<tr>
<td>GALEX</td>
<td>FUV, NUV</td>
<td>1 sq.deg.</td>
<td>26 AB mag</td>
<td>100% complete, GTO</td>
</tr>
<tr>
<td>GALEX</td>
<td>FUV, NUV</td>
<td>9 sq.deg.</td>
<td>25 AB mag</td>
<td>in progress, GTO</td>
</tr>
<tr>
<td>HST</td>
<td>I, H</td>
<td>sparse</td>
<td>26, 23 mag</td>
<td>in progress</td>
</tr>
<tr>
<td>Chandra</td>
<td>0.5-2 keV</td>
<td>9 sq.deg.</td>
<td>4.7e-15 erg/s/cm²</td>
<td>100% complete</td>
</tr>
<tr>
<td>Chandra</td>
<td>2-7 keV</td>
<td>9 sq.deg.</td>
<td>1.5e-14 erg/s/cm²</td>
<td>100% complete</td>
</tr>
<tr>
<td>NOAO/Keck</td>
<td>spectroscopy</td>
<td>sparse</td>
<td>24 mag</td>
<td>in progress (400 so far)</td>
</tr>
<tr>
<td>MMT/Hectosp</td>
<td>spectroscopy</td>
<td>9 sq.deg.</td>
<td>R~20.5 mag</td>
<td>completed</td>
</tr>
<tr>
<td>Spitzer/IRS</td>
<td>spectroscopy</td>
<td>sparse</td>
<td></td>
<td>in progress</td>
</tr>
</tbody>
</table>
The Spitzer surveys in Bootes

MIPS Survey (24, 70, 160 µm)
limits: 0.3mJy, ~30mJy, ~100mJy
PIs: T. Soifer, M. Rieke

IRAC Shallow Survey (3.6, 4.5, 5.8, 8 µm)
Limits: 6.4, 8.8, 51, 50 µJy
PIs: P. Eisenhardt, G. Fazio
R-[24]>14: Dusty, obscured galaxies

R-[24]>14 sources - a magnitude redder than Arp 220 out to high redshifts.

- 2000 (5% of the 24µm sources) with R-[24]>14
- If at z~2 as IRS follow-up suggest, \( L_{\text{bol}} \sim 10-100 \times L_{\text{Arp220}} \) but fainter than 0.1L* galaxy in the optical.
  - no comparable examples in the local Universe.
Houck et al. (2005)

- Spitzer/IRS spectra of f_{24} > 0.8 mJy sources
  - z ~ 2 - 2.6
  - ~50% have silicate absorption features. No PAH emission.
  - L_{IR} ~ 1 \times 10^{13} L_{\odot}

Houck et al. (2005)
Near-IR spectra of R-[24]>14 sources

Broad-line AGN

Brand et al. 2007
Near-IR spectra of R-[24]>14 sources

- 10 sources detected with Keck NIRSPEC / Gemini NIRI
- All sources at 1.3<z<3.4
- All sources AGN - dominated
- 7/10 broad-line, 3/10 narrow-line AGN
- Hα/Hβ ratios → A(Hα)> 2.4 - 5 magnitudes
- Both broad and narrow lines obscured - Obscuration on scales larger than torus
- Faint UV-continuum emission → obscuration on ~kpc scales
IRS spectra of ‘bump’ sources

$f_{24} > 0.8$ mJy galaxies have power-law SEDs.

$f_{24} = 0.3-0.8$ mJy galaxies show pronounced 1.6um “bump” from old stellar population.

IRS spectra show strong PAH emission - Starburst-dominated galaxies.

Desai et al. in prep.
The number density of R-[24]>14 sources

• Brown et al. - 130 optically bright quasars in Bootes field at z>1.3
• 340 R-[24]>14 sources with $f_{24}>1\,\text{mJy}$. Assuming they are all z>1.3 AGN, twice as common as optically bright sources (or dusty obscured phase is twice as long as optical quasar phase).
• ~1500 R-[24]>14 sources with $f_{24}=0.3$-0.8mJy. ~ 4 times as many dusty starburst dominated sources.
• Number density much smaller than that of massive (>10^{11} solar masses) galaxies in local Universe.
  → May represent progenitors of the most massive galaxies, viewed in a brief phase of rapid spheroid and BH growth.
Summary

• A large fraction of today’s massive old galaxies assembled at high z.
• R-[24]>14 selects z>1.5 galaxies undergoing intense star-formation and AGN activity
• $f_{24}>0.8\text{mJy}$ sources are AGN-dominated. Near-IR spectroscopy shows that
  – The fraction of type 1 to type 2 source is consistent with receding torus models.
  – optical extinction extends over broad- and narrow-line regions.
  – Faint rest-UV luminosities suggest that optical extinction may be on ~kpc scales and that these are ‘host obscured’ AGN
• $f_{24}=0.3-0.8\text{mJy}$ sources are mostly starburst-dominated galaxies. May be massive galaxies undergoing rapid spheroidal growth.
HST imaging of R-[24]>14 sources

Much of optical extinction is on ~kpc scales within the host galaxy itself
Log($\nu f_\nu(24)/ \nu f_\nu(8)$) distributions for different $f_\nu(24)$ bins

Brand et al. 2005
The fraction of AGN dominated ULIRGs as a function of $f_{24}$

24$\mu$m number counts from Papovich et al. 2004 -> AGN contribute to $\sim$5-13% of the 24 $\mu$m background.