Galaxy Formation: The Radio Decade
(Dense Gas History of the Universe)
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Santa Fe, March 2011

• Power of radio astronomy: dust, cool gas, and star formation

• Epoch of galaxy assembly (z~1 to 3)
  ➢ Massive galaxy formation: dust obscured, hyper-starbursts
  ➢ Early disk galaxy formation: gas dominated galaxies

• Bright (immediate!) future: The Atacama Large Millimeter Array and Expanded Very Large Array, with recent examples
Star formation history of the Universe
(mostly optical/near-IR view)

~50% of present day stellar mass produced between z~1 to 3

Epoch of galaxy assembly

First light + cosmic reionization

Cosmic demise

Bouwens +
Star formation history as a function of $L_{\text{FIR}}$ ($\sim$ SFR)

- $L_{\text{IR}}^{\text{noAGN}} + $ Comp. Correction
- $L_{\text{IR}} < 10^{11}L_\odot$
- LIRGs: $10^{11}L_\odot \leq L_{\text{IR}} < 10^{12}L_\odot$
- ULIRGs: $L_{\text{IR}} \geq 10^{12}L_\odot$

$\rho_{L_{\text{IR}}} (L_\odot \text{ Mpc}^{-3})$

$\rho_{\text{SFR}} (M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3})$

- SFR $< 30$ M$_\odot$/yr
- SFR $> 300$ M$_\odot$/yr

Murphy ea
Optical Limitation 1: Dust

Dust correction in UV:
- Factor 5 at $z < 4$
- No correction at $z > 6$?
Optical Limitation 2: Cold gas = fuel for star formation
(‘The missing half of galaxy formation’)

Integrated Kennicutt-Schmidt star formation law: relate SFR and gas content of galaxies

Non-linear => gas consumption time (M_{gas}/SFR) decreases with SFR

Low and high z starbursts \( t_c < 10^7 \) yr

Low z spirals \( t_c > 10^8 \) yr

Power-law index = 1.5

Wang
Millimeter through centimeter astronomy: unveiling the cold, obscured universe

- cm/mm reveal the dust-obscured, earliest, most active phases of star formation in galaxies
- cm/mm reveal the cool gas that fuels star formation
100 M$_{\odot}$ yr$^{-1}$ at $z=5$

- Low J CO emission: total gas mass, dynamics
- High density gas tracers (HCN, HCO$^+$)
- Synch. + Free-Free = star formation

- High J molecular lines: gas excitation, physical conditions
- Dust continuum = star formation
- Atomic fine structure lines: ISM gas coolant
Today’s focus: molecular gas

- 115 CO detections at $z > 1$ published to date
- $\sim 50\%$ in the last 2 years
  - PdBI improvements; EVLA, GBT Zpectrometer
  - Discovery of gas rich ‘normal’ SF galaxies $z \sim 2$

Hyper-starbursts
($L_{FIR} > 10^{13} L_\odot$)
SMGs/QSOs

Normal disks
$L_{FIR} \leq 10^{12} L_\odot$
sBzK/BX-BM

Reichers
Hyper-starbursts at high redshift: Submm galaxies, and (~ 1/3) Quasar hosts

- $S_{250} > 3\text{mJy} \Rightarrow L_{\text{FIR}} > 10^{13}L_\odot \Rightarrow \text{SFR} > 10^3 \text{M}_\odot/\text{yr}$
- $<\text{FWHM}>_{\text{SMG}} = 800\text{km/s}$
- $M(\text{H}_2) \sim 10^{10-11} (\alpha/0.8) \text{M}_\odot$
- $M(\text{dust}) \geq 10^8 \text{M}_\odot$
- Gas consumption times $\sim 10^7 \text{yrs}$
- CO compact ($<\text{few kpc}$) and chaotic in velocity
- Rare: 1 SMG per 20 arcmin$^{-2}$
• **SLED:** LVG model $\Rightarrow T_k > 50$K, $n_{H2} = 2 \times 10^4$ cm$^{-3}$
  - Galactic Molecular Clouds (50pc): $n_{H2} \sim 10^2$ to $10^3$ cm$^{-3}$
  - GMC star forming cores ($\sim$1pc): $n_{H2} \sim 10^4$ cm$^{-3}$

• **SED:** Warm dust $\sim 30$ to $50$ K, follows Radio-FIR correlation $\Rightarrow$ SFR $> 10^3$ M$_o$/yr
SMGs and Quasar hosts: Building large elliptical galaxies (and SMBH) in major gas rich mergers

- Stellar mass $\geq 10^{11} M_\odot$ forms in a few gas rich mergers starting, driving SFR $>10^3 M_\odot$/yr
- SMBH of $\sim 10^9 M_\odot$ forms via Eddington-limited accretion + mergers
- Evolves into giant elliptical galaxy in massive cluster ($\sim 10^{14-15} M_\odot$) by $z=0$

- Rapid enrichment of metals, dust in ISM (seen at $z > 6$)
- Rare, high mass objects
- Goal: push to normal galaxies at high redshift

Li, Hernquist+
Formation of disk galaxies during epoch of galaxy assembly

sBzK/BX-BM at $z \sim 1$ to 3

- HST + Hα imaging $\Rightarrow$ ‘messy disk’ $\sim 10$ kpc, punctuated by massive star forming regions (Genzel, Tacconi, Daddi)

- Color-color diagrams identify thousands of $z \sim 2$ star forming galaxies

- SFR $\sim 10$ to $100$ $M_\odot$/yr, $M_* \geq 10^{10}$ $M_\odot$

- Common $\sim$ few $\times 10^{-4}$ Mpc$^{-3}$ (5 arcmin$^{-2}$) $\sim 100x$ SMG
CO observations with Bure:
Massive gas reservoirs without extreme starbursts (Daddi et al. 2010)

- 6 of 6 z~2 sBzK detected in CO
- Gas mass \( \sim 10^{10-11} M_\odot \sim \) gas masses in SMG/Quasar hosts

but

- SFR < 10% less \( (S_{250} < 1\,\text{mJy}) \)

(see also UV-selected BX/BM galaxies in Tacconi et al.)
BX/BM: PdBI imaging (Tacconi ea)

• CO galaxy size ~10 kpc

• Clear rotation: $v_{\text{rot}} \sim 200 \text{ km/s}$

• SF clump physics
  - Giant clumps > 1 kpc
  - $M_{\text{gas}} > 10^9 M_\odot$
  - Turbulent: $\sigma_v \sim 20 \text{ km/s}$
- Lower CO excitation: low J observations are key!
- FIR/L\textsuperscript{'} CO: Gas consumption timescales $\sim$ few $\times 10^8$ yrs

$\Rightarrow$ Secular galaxy formation during epoch of galaxy assembly
Baryon fraction is dominated by gas, not stars

\[ M(\text{H}_2) \geq M_\ast \]

Caveat: using \( \alpha = 4 \sim \) MW value

- Dynamical modeling include DM (Bournaud)
- MW excitation
- MW FIR/L' CO
- MW disk sizes

(see Daddi ea, Tacconi ea)

Needs confirmation!
Emerging paradigm in galaxy formation: cold mode accretion (Keres, Dekel…)

- Galaxies smoothly accrete cool gas from filamentary IGM onto disk at \( \sim 100 \, M_\odot/\text{yr} \) (high density allows cooling w/o avoid shock heating)

- Form turbulent, rotating disks with kpc-scale star forming regions, which migrate inward over \( \sim 1 \) Gyr to form bulge

- Fuels steady star formation for \( \sim 1 \) Gyr; Feedback keeps SFR < accretion rate

‘Dominant mode of star formation in Universe’
Fundamental change in galaxy properties during peak epoch of galaxy formation: Epoch of galaxy assembly = epoch of gas dominated galaxies.
Atacama Large Millimeter Array

- High sensitivity array = 54x12m
- Wide field imaging array = 12x7m
- Frequencies = 80 GHz to 900 GHz
- Resolution = 20mas at 800 GHz
- Sensitivity = 13uJy in 1hr at 230GHz

ALMA+EVLA represent an order of magnitude, or more, improvement in observational capabilities from 1 GHz to 1 THz!

Expanded Very Large Array

- 80x Bandwidth (8 GHz, full stokes), with 4000 channels
- Full frequency coverage (1 to 50 GHz)
- 10x continuum sensitivity (<1uJy)
- Spatial resolution ~ 40mas at 43 GHz
ALMA and first galaxies: [CII] into reionization

- $z > 7$ galaxies $\sim 100$ to date
  - $0.3$ arcmin$^{-2}$
  - SFR $\sim$ few $M_\odot$/yr
  - Difficult to get $z_{\text{spec}}$
- ALMA can detect [CII] in a few hours $= \text{redshift machine!}$ $[dz = 0.27]$
As a test of ALMA’s ability to observe broad spectral lines, we observed the quasar BRI 0952-0115, which is at a red-shift of $z = 4.43$. The object is again unresolved on short baselines, but the 158 micron line from ionized carbon is clearly detected in the spectrum, which is impressive given that this observation took only one hour in total.
ALMA: Detect multiple lines, molecules per 8GHz band = real spectroscopy/astrochemistry

EVLA: 30% FBW, ie. 19 to 27 GHz (CO1-0 at z=3.2 to 5.0) => large cosmic volume searches for molecular gas (1 beam = $10^4$ cMpc$^3$) w/o need for optical redshifts
EVLA/ALMA Deep fields: the ‘missing half’ of galaxy formation

- Volume (EVLA, z=2 to 2.8) = 1.4e5 cMpc$^3$
- 1000 galaxies z=0.2 to 6.7 in CO with M(H$_2$) > 10$^{10}$ M$_{\odot}$
- 100 in [CII] z ~ 6.5
- 5000 in dust continuum

Table 1: EVLA (30-38GHz), ALMA (90-98GHz), 1000hrs, 50arcmin$^2$

<table>
<thead>
<tr>
<th>Transition</th>
<th>$z_{\text{range}}$</th>
<th>Number of Galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALMA CO 1-0</td>
<td>0.17 to 0.27</td>
<td>40</td>
</tr>
<tr>
<td>ALMA CO 2-1</td>
<td>1.3 to 1.6</td>
<td>389</td>
</tr>
<tr>
<td>EVLA HCN 1-0</td>
<td>1.3 to 2.0</td>
<td>7</td>
</tr>
<tr>
<td>EVLA HCO$^+$ 1-0</td>
<td>1.3 to 2.0</td>
<td>7</td>
</tr>
<tr>
<td>EVLA CO 1-0</td>
<td>2.0 to 2.8</td>
<td>130</td>
</tr>
<tr>
<td>ALMA CO 3-2</td>
<td>2.5 to 2.8</td>
<td>122</td>
</tr>
<tr>
<td>ALMA CO 4-3</td>
<td>3.7 to 4.1</td>
<td>66</td>
</tr>
<tr>
<td>ALMA CO 5-4</td>
<td>4.9 to 5.4</td>
<td>24</td>
</tr>
<tr>
<td>EVLA CO 2-1</td>
<td>5.0 to 6.7</td>
<td>13</td>
</tr>
<tr>
<td>ALMA CO 6-5</td>
<td>6.0 to 6.7</td>
<td>7</td>
</tr>
<tr>
<td>ALMA(250GHz) [CII] 158um</td>
<td>6.36 to 6.6</td>
<td>110</td>
</tr>
<tr>
<td>ALMA(250GHz) Continuum</td>
<td>$z &lt; 10$</td>
<td>5000</td>
</tr>
</tbody>
</table>

New horizon for deep fields!

Millennium Simulations
Obreschkow & Rawlings
GN20 molecule-rich proto-cluster at z=4
CO 2-1 in 3 submm galaxies, all in one pointing, 256 MHz band

Every observations at > 20 GHz will discover new galaxies!
Dense gas history of the Universe → Tracing the fuel for galaxy formation over cosmic time

Millennium Simulations
Obreschkow & Rawlings
See also Bauermeister et al.

DGHU is primary goal for studies of galaxy formation this decade!
Major questions

- $L'_\text{CO}$ to H$_2$ mass conversion factor: calibrate dynamically? Bivariate? [low order CO imaging]
- Universality of star formation laws? [Dust/CO imaging]
- Gas supply: CMA or mergers (or a bit of both?) [CO imaging?]
- Dust formation within 1Gyr of the Big Bang? [submm continuum $z > 7$ candidates]
- [CII] as a redshift machine? [ALMA!]
- Dense gas fraction: SF efficiency (HCN, HCO+)
- Driving SFR $> 10^3$ M$_\odot$/yr (maximal starburst, AGN)? [SED, Free-Free]
Star formation as function of stellar mass

specific SFR = $\frac{SFR}{M_*} \sim$ e-folding time$^{-1}$

\[ \log_{10} \left( \frac{\langle SFR \rangle}{M_*} \right) \ (Gyr^{-1}) \]

Zheng ea

‘Downsizing’ : Massive galaxies form most of stars quickly, at high $z$

(see also: stellar pop. synthesis at low $z$; evolved galaxies at $z \sim 1$ to $2$)
\( \log \frac{L_{\text{CII}}}{L_{\text{FIR}}} \) vs. \( \log L_{\text{FIR}} (L_{\odot}) \)

- Normal Galaxies (Malhotra et al 2001)
- Local ULIRGs (Luhman et al 1998)
- High-z samples
  - \( z > 2.3 \)
  - \( z = 1-2 \) SF
  - \( z = 1-2 \) AGN
  - \( z = 1-2 \) mixed

- \( F(60)/F(100) \)
CCAT: wide field ‘finder’ surveys

Figure 1: Point-source survey speed (rate at which sky can be mapped for point sources in units of arcmin$^2$/mJy/hour for a one-sigma detection) for CCAT and ALMA vs. wavelength). CCAT assumes a 150×150 focal plane array sampling two pixels/beam.
Lower CO excitation: low J observations are key!

FIR/L’ CO: Gas consumption timescales $\geq$ few $\times 10^8$ yrs
Molecular gas mass: $X$ factor

- $M(H_2) = X \ L' (CO(1-0))$

- Milky way: $X = 4.6 \ M_\odot/(K \ km/s \ pc^2)$ (virialized GMCs)

- ULIRGs: $X = 0.8 \ M_\odot/(K \ km/s \ pc^2)$ (CO rotation curves)

- Optically thin limit: $X \sim 0.2$

![Diagram showing intensity and velocity contours for VII Zw 31 and CO(1-0) lines with Downes + Solomon labels.]
X factor $sBzK = MW$: dynamics + modeling
• SLED: LVG model => $T_k > 50 K$, $n_{H_2} = 2 \times 10^4$ cm$^{-3}$
  - Galactic Molecular Clouds (50pc): $n_{H_2} \sim 10^2$ to $10^3$ cm$^{-3}$
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Reichers 2010