RADIO AND MILLIMETRE STUDIES OF HIGH-REDSHIFT GALAXIES

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Millimetre (ALMA) and Radio (JVLA)

Sub-arcsecond resolution, extinction-free, sensitive tracers of star formation $z=1-7$
Canadian ALMA/JVLA high-z science

• We have some amazing science leaders in Canada working on high-z galaxies.
• Gas in $z \sim 1.5$ brightest cluster galaxies (Webb, Noble, Bonaventura …)
• $z \sim 6$ ALMA QSOs (Willott+2013) and galaxies (Willott+2015,2017)
• Major representation in the 2 large deep field projects
  • D.Scott in ALMA-UDF (PI: J. Dunlop)
  • S.Chapman in ASPECS (PI: F. Walter)
• Strong representation in Herschel, SPT and Planck surveys (D.Scott, S.Chapman)
• Leadership and good representation in JCMT Cosmology Legacy surveys and ALMA/SMA/JVLA followup programs
  • D.Scott / S.Chapman PI’s and regional leaders for different programs
  • T.Webb, M.Sawicki, A.Babul, C.Wilson, … all involved in JCMT programs.
Brightest Cluster Galaxies

- LMT detected CO(2-1) gas in BCG at $z=1.7$ (Webb et al. 2017)
  - largest gas reservoir ever detected in a BCG $z>1$
  - Cooling flow or galaxy merger(s)?

T. Webb (McGill): Tremendously productive group working on mm/farIR in $z\sim 1-2$ clusters
# Brightest Cluster Galaxies

(Bona Ventura, TW, et al. 2017)

<table>
<thead>
<tr>
<th>IRAC 3.6µm 19.8″</th>
<th>IRAC 4.5µm 19.8″</th>
<th>IRAC 5.8µm 19.8″</th>
<th>IRAC 8µm 19.8″</th>
<th>MIPS 24µm 15.75″</th>
<th>MIPS 70µm 48″</th>
<th>MIPS 160µm 96″</th>
<th>PACS 100µm 14.4″</th>
<th>SPIRE 250µm 65.8″</th>
<th>SPIRE 350µm 90″</th>
<th>SPIRE 500µm 126″</th>
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Brightest Cluster Galaxies

Noble + TW, et al. 2017
-- lie systematically off the field scaling relations at z~1.6
-- Gas fractions mimic the strong rise with redshift in the field
The holy grail of high-z galaxies in millimetre

Galaxies get brighter beyond z~1.5 !!!

Not affected by obscuration (the way optical is)

850um \hspace{2cm} \text{e.g., JCMT}

2mm \hspace{2cm} \text{e.g., SPT}
ALMA: *15min at 358GHz* gets us this *z=4.3* structure (no shred of optical emission, faint IRAC 4um emission)

-- 14 [CII] emitting galaxies in 130kpc region
-- Down to 30M/yr
-- Even at z=4.3, still a bit more sensitive in C+ than continuum

(of course full Cy3,4,5 program is 30hrs!)
SPT2349: $z \approx 4.3$, highest density, most luminous structure known in Universe

Brightest source is huge turbulent disk

Chapman et al. – submitted to Nature
20min with ALMA at 240GHz gives us \( \textbf{z=7} \) discoveries…

- \( \textbf{z\sim7} \) redshift record for SMGs
- Detailed fine structure astrophysics on a massive, optically invisible merger
- Companion is actually a moderate SF’er (30M/yr)

D. Marrone et al. +SCC (Nature – in press)
But ALMA followup of these sources is the end of the story!

Feeding millimetre surveys: ALMA can’t map

(why did we give up JCMT to get ALMA !?!) 

- So where do we find these sources: 
- Single dish mapping with wide fields (JCMT, APEX, SPT, IRAM, LMT)
The South Pole Telescope survey

(Provocative point, as only “me” in SPT – Matt, Keith in SPT could work on SMGs)

The South Pole Telescope

PI: John Carlstrom

Goal: Cosmological survey to study CMB fine structure and Sunyaev–Zel'dovich signal from Galaxy clusters

Area: 2500 deg$^2$

Wavelengths: 3, 2 and 1.4 mm (typical rms at 1 mm ~3.5 mJy)

Bonus: Large sample of rare ultra bright sources

Vieira+08

Funded by NSF

Carlstrom et al. 2011
The z=4.3 protocluster SPT2349 Discovery

- Unique source in 2500 deg$^2$ SPT-SZ survey. All others are lensed SMGs or weaker. *SPT2349-56 not even detected with Planck.*

**SPTpol 2mm : 4 deg$^2$**

(a S2-CLS footprint)

Resolved by LABOCA (20") and even by SPT (1’).
SPT SMGs: High-redshift star formation under the cosmic microscope

Joaquin Vieira
The University of Illinois at Urbana-Champaign
SMG20, Durham
02 August 2017
• ALMA cy0,1,3,4 Redshift survey finally complete with 85 SPT sources
ALMA
SDP 81
z=3.042
30 milli-arcsecond resolution 1-mm

Data like this coming for 3 SPT sources soon!
EGS

UDS

Lockman Hole

SSA22

Akari-NEP

COSMOS

No SMA

JCMT

SCUBA-2

5 deg^2

EGS

S2-CLS: Geach et al.

2016, 2017

(+TW, DS, SCC, MH, ...)

1 degree
S2-CLS followup: ALMA program (PI: Smail) SMA program (PI: Chapman)

- observe all 150 S2-CLS sources with S850>9mJy (~1000 Msun/yr)
- In UDS all 1000 S2-CLS sources >3.5sigma
- ~few hours with ALMA;
- 31 tracks/night with SMA
  - compact (~2") 860um observations over 5 proposals and 2.5years;
  - Major commitment from SMA

Simpson et al. 2015. in prep; Hill, SCC, DS, et al. 2017

Examples in AEGIS
Multiwave properties

~1 degree

SCUBA-2 850um
S2-CLS counts, SMA/ALMA identified
(Hill, Chapman, Scott et al. 2017)

- Counts show more bright single sources than early (ALMA) studies suggested
  - ECDFS / A-LESS (Hodge/Karim2013) just doesn’t have bright single sources.
- Simulations of course rapidly adapting to fit data.

- ~10% signs of being lensed (R.Perry etal)
Extreme SMGs: Brightest (unlensed) sources in S2-CLS ~5deg\(^2\)

- COS1 (as verified by s2cosmos); \(S_{\text{SCUBA2}}=21\text{mJy}\); single SMA ID S870=19mJy
- SMA (green) and VLA (red); IRAC image
- Mild Multiplicity (19 + 3 mJy)
- Keck LRIS shows \(z=2.5\) (single line \(Ly\alpha\))

Previous brightest ~20mJy SCUBA(2) sources:
- GN20 looks like single massive disk
- H1700-Harriet looks like close major merger

These were found at 850\(\mu\)m in 100 arcmin\(^2\) surveys!
The holy grail of high-z galaxies in millimetre

MM galaxies get brighter beyond z~1.5 !!!

WHAT ABOUT RADIO?
K-correction similarly “bad” to opt/nearIR
Since the FIR-Radio correlation seems to hold to high redshifts . . .
(Note: below excludes any sources with observed-frame 4-8 keV counterparts from CDF-N, but still substantial AGN contamination)

Red: $z=1.6-4$
Black: $z=0.8-1.6$
Blue: $z=0.4-0.8$
Green: $z=0.2-0.4$

$q=2.36$
JVLA/millimetre synergy

(Barger+2015, Cowie+2017)

Used together, submm and radio data become much more powerful – e.g., we can pick out which sources in the high radio power sample are high-redshift star formers based on their submm detections.
HUDF deep survey 4.5 sq. arcmin

Jansky VLA  5 cm, 0.3 μJy/beam rms
16 sources in VLA, not in ALMA
11 sources in ALMA and VLA
177hrs

ALMA  1.3 mm, 29 μJy/beam rms

~10hrs today

HUDF

WR+16
Dunlop, WR+17
Deep Fields

Why *both* VLA and ALMA?

- $177^{th}$ VLA is more sensitive to SF at $z < 2.6$; ALMA $20^{th}$ wins at $z > 2.6$ — need both to cover the peak of galaxy assembly ($z \sim 1 - 3$).

- VLA: SF + AGN
  - ALMA: dust associated to SF; generally AGN-free

- Map SFR, cold dust, and in some cases, pinpoint radio AGN
As above, ALMA is not a great mapping instrument

Blind spectral line surveys in [CII] at z~6, and CO z~1-3
Very small field within above ECDFS

Walter+16, Decarli+16, Aravena+16 +SCC
JVLA 1uJy @ 3GHz

Condon (+DS) et al. 2012
“RESOLVING THE RADIO SOURCE BACKGROUND: DEEPER UNDERSTANDING THROUGH CONFUSION”

Vernstrom,DS,Wall 2011
“Contribution to the Diffuse Radio Background from Extragalactic Radio Sources”
Challenges in pinpointing the sites of SMBH accretion

X-ray is \( \sim 1'' \) resolution; optical indicators are limited to \( \sim 0.1'' \) of IFUs and may be obscured — Radio is the only way to localize AGN to sub-kpc at \( z \sim 2 \)

**VLA/14A-360**

4 - 8 GHz, 177h integration

- \( z = 3.0 \)
- \( z = 2.9 \) SFG
- \( z = 2.7 \) Radio AGN

5''

**Hubble**

1.25, 1.40, 1.60 \( \mu \)m

- 326 M\( \odot \)/yr
- 247 M\( \odot \)/yr
- 56 M\( \odot \)/yr

**Chandra**

0.5 - 8 keV, 4 Ms integration

- X-ray AGN

*Chandra* PSF is 0.7 - 3.6'' at off axis angles of 1' - 9'; VLA C-band/A-array is 0.3''

Rujopakarn et al. 2016
Radio emission well over the level implied by the far-IR/radio correlation pinpoints the AGN

AGN can be located down to $\theta_{\text{beam}}/(2 \times \text{SNR})$, better than 5 mas in this case

Rujopakarn et al. 2016
Conclusions

- Lots of amazing high-z galaxy radio/millimeter science!
- We should get lots of young people involved and building this field towards future facilities
- ALMA is super powerful (sensitive and K-correction),
- … but needs single dish telescopes to tell it where to point!
- Does radio have a roll still? K-correction in millimeter for hi-z
- Radio on it’s own (without Millimetre) pales for z>2 star forming galaxies, but is powerful tool (wider fields, AGN and SFdiagnostics)
- HI aside, Radio provides unique lines – CO(1-0) at hi-z.
- For blind deep fields of any area, radio can be very important: ECDFs (even when ALMA puts huge amounts of time to it)