The first galaxies with

Françoise Combes
Observatoire de Paris
8 Mars 2010
Capacities of ALMA

50 x 12m, bases from 200m to 14km, 3mm to 0.3mm (factor ~6 in surface with respect to IRAM-PdB)
+ 4 antennae of 12m + 12 antennae of 7m ACA (Japan)
4 frequency bands at the beginning
84-116 GHz, 211-275 GHz, 275-370 GHz, 602-720 GHz
Large bandwidth of 8GHz/polar

Spatial resolution, up to 10mas,
Spectral resolution up to $R=10^8$
Dynamical range from 128x128 to 8192x8192 pixels

Small field of view: from 1arcmin (3mm) to 6 arsec (0.3mm)
Possibility of mosaics

Early Science 2011? In 2012-3: Full Operation
Main privilege of the mm/submm domain

Negative K-correction: example of Arp 220
Continuum detections

30% Quasars @ z=6 detected in continuum $\Rightarrow$ HLIRG > $10^{13}L_0$
Mdust $\sim 10^8$ Mo, means that dust forms early in the universe

Omont 2009
Detecting CO in galaxies at high redshift with ALMA

=> For high z galaxies, go to low frequencies
  z=6 CO(7-6) at 3mm

=> At 3mm (115GHz), field of 1 arcmin x 1 arcmin
Most frequently 300x 300 = 90 000 pixels/spectra

Bandwidth 2x 8GHz ~ 16%, or ~50 000km/s
Possibility to have several lines from the
Rotational ladder of CO, or other molecules..

@z =6, the spacing between CO lines is of 16 GHz.
With 2 tunings, one obtains a « redshift-machine »
Z=3 ULIRGs easy to detect with ALMA

$M(H_2) = 6 \times 10^{10} M_\odot$, $N(H_2) = 3.5 \times 10^{24}$ cm$^{-2}$, $\text{CO}/H_2 \sim 10^{-4}$

$\frac{n_H^2}{cm^{-3}} = 10^3$

$\frac{n_H^2}{cm^{-3}} = 10^4$

$\frac{n_H^2}{cm^{-3}} = 10^5$

$\frac{n_H^2}{cm^{-3}} = 10^6$

Influence of density

Size = 1 kpc

Log Flux (mJy)

Log $\lambda_{\text{obs}}$ (mm)
Predictions for LBG at $z \sim 3$: ALMA 24h, 0.1"

Greve & Sommer-Larsen 2008

rms=10 μJy/beam (2-3 σ)
Predictions Line sensitivity $z=5$

Carilli 2006
Molecular Absorptions (mm & cm)

Up to now, only 5 systems: PKS1413, B3 1504 (self-abs) B0218, PKS1830, PMN J0134 (OH): gravit lenses + local: CenA, 3C293 (0.045), 4C 31.04 (0.06)

Chemistry @highz
Variations of cst

~ 30-100 times more sources with ALMA?

Combes & Wiklind 1998
Cosmic evolution of the CO-LF

With some hypothesis, about the H2/HI ratio in galaxies
More H2, due to more compact and gaseous galaxies

Heating by SB AGN, CMB
Metals, smooth or clumpy
Overlap of clouds, etc..

Obreschkow et al 2009
Cosmic evolution of H2/HI

The HI evolution is taken from absorbants, but could be biased

Pressure-based model for H2

Simulations from a catalog of Millenium, + SAM

H2/HI \sim (1+z)^{1.6}

Obreschkow & Rawlings 2009
Observations of CO lines

CO emission: ~70 sources at high z (2010)

1st historical detection: Faint IRAS source F10214+4724 at z=2.3 (Brown & van den Bout 92, Solomon et al 92)

Downes et al 95
Properties of high-z galaxies

Iono et al 2009  Good correlation  LFIR/LCO (even for QSO)
Kinematics and mass

$M_{H_2} = 6 \times 10^{10} \text{M}_\odot$

$M_{\text{dyn}} = 3.0 \times 10^{11} / \sin^2 i \text{M}_\odot$

$M_{\text{bh}} = 6 \times 10^8 \text{M}_\odot$

$\Delta V = 1100 \text{km/s}$

SMM J2399-0136

Frayer et al (1998) CO(3-2)

$z=2.808$


Amplification of 2.5
z> 4 galaxies in CO

Almost all amplified!

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>z</th>
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<tr>
<td>PSS J2322 +1944</td>
<td>QSO</td>
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<td>SDSSJ1148+5251</td>
<td>QSO</td>
<td>6.419</td>
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</table>

+ 6 z=6 QSO (Wang et al 2010)
The most distant QSO at $z=6.4$

- Beam 0.3" PdB
- Age ~ 1 Gyr
- Keck z-band
- Djorgovski et al.

Fan et al 2003, White et al 2003
$M_{\text{dust}} \sim 10^8 \text{Mo}$ (Bertoldi et al 2003)
$M_{\text{BH}} = 1.5 \times 10^9 \text{Mo}$ (Willot et al 2003)
No HCN detected
CII, Walter et al 2009
1kpc scale starburst, 1000Mo/yr/kpc$^2$
High density tracers

HCN appears better correlated to star formation than CO

CI is detected, CII is proportionally weaker in ULIRGs

Gao & Solomon
2004
Molecular gas at >kpc scale

Gas-rich mergers of galaxies, 1.4 Gyr after the Big-Bang

5 kpc extent $>>$ local ULIRG

$M_{H_2} = 9.2 \times 10^{10} M_\odot$

$M_{dyn} = 1.0 \times 10^{11} / \sin^2 i M_\odot$

$M_{bh} = 6 \times 10^9 M_\odot$ (Edd limit)

Riechers et al 2008
Molecular gas in Einstein ring

Gas-rich mergers of galaxies
z=4.12, 5kpc extent
BH offset

VLA, CO(2-1), SFR= 680 Mo/yr
Riechers et al 2008

MH$_2$ = 1.7 $10^{10}$ Mo
Mdyn = 4.4 $10^{10}$ /sin$^2$iMo
Mbh = 1.5 $10^9$Mo (Edd limit)

Mbulge = 30 Mbh
Too high BH masses!
Eddington limited star formation

SFR $\sim$500-1000 $\text{Mo/yr/kpc}^2$

$z>4$ QSO hotsts, 5kpc scale

Dust opacity limited $\Sigma$ disk SFR

Comparable to local ULIRGs

GMC $\sim$200$\text{Mo/pc}^2 = 10^{22} \text{H}_2/\text{cm}^2$

$\sim$2 $10^8\text{Mo/kpc}^2$

$\text{NH}_2 \sim 10^{24}\text{cm}^{-2}$

$n\text{H}_2 \sim 10^4 \text{cm}^{-3}$

Riechers et al 2009
Moderate SFR: Cosmic eye

LBG @z=3.07  P de Bure CO(3-2) detection
(only the 2nd LBG, after cB58)
MH2 = 2.4 \times 10^9 \, \text{Mo}  \quad M^* = 6 \times 10^9 \, \text{Mo} \quad \text{(Spitzer mid-IR)}

SFR = 60\,\text{Mo/yr} \quad \text{life-time} = 40\,\text{Myr}
High-z analog of LIRGs

Magnification of 28
2 UV components, 3kpc apart
Coppin et al 2007

Dynamical mass \sim 10^{10} \, \text{Mo}
But inclination uncertain

HST ACS
Star formation rate in LBGs

SFE $\sim 140$ Mo/Lo

LCO & gas mass 7 times higher than cB58

$z=2.73$

8 o'clock arc
Allam et al 2007
SMGs: Submillimeter Galaxies
Star formation efficiency $L_{\text{IR}}/L_{\text{CO}}$ vs $z$

Greve et al 2005

6 SMGs not detected in CO

40- 200 Myr SB phase
SFR $\sim$700 $M_\odot$/yr
More efficient than ULIRGs

Mergers without bulges?

Total masses $\sim$0.6 $M_\star$
Low efficiency of star formation

In BzK galaxies, much more CO emission detected than expected. Massive galaxies, CO sizes 10kpc? $L(\text{FIR}) \sim 10^{12}\, L_\odot$.

Normal SFR, $M(\text{H}_2) \sim 2 \times 10^{10}\, M_\odot$ $\tau \sim 2\, \text{Gyr}$

→ Much larger population of gas rich galaxies at high $z$

Daddi et al 2008
Low excitation, MW-like

In BzK-21000, $z=1.52$, weak CO(3-2) → CO conversion factor 4.5 x that of ULIRGS (MH2/LCO)

Dannerbauer et al 2009
Large range in BzK galaxies

Another SF BzK not detected in CO: wide range of properties

Hatsukade et al. 2009
19 galaxies observed at IRAM, 10 at z~2.3 and 9 at z~1.2

High detection rate >75%, in these « normal » massive Star Forming Galaxies (SFG)
Gas content ~34% and 44% in average at z=1.2 and 2.3 resp.

Tacconi et al 2010, Nature
SFR proportional to $M_*^{0.8} (1+z)^{2.7}$

And also a little bit from a higher SF efficiency with redshift

$\Rightarrow$ Galaxies must continuously accrete mass

Tacconi et al 2010, Nature
Redshift Machine

Always a line in 80-116Ghz, if $z>2.2$
Difference between 2 lines depend on J

SMMJ14009+0252.

Weiss et al 2009
Excitation in high-z starbursts

Weiss et al 2007
z> 7 sources: ALMA CO discovery space

Walter & Carilli 2007
Other lines CII $158\mu$, CI, NII...

CI/H$_2$ $\sim 10^{-5}$

CII/LFIR $\sim 0.06\%$, 10 times less than locally

CII detected in J1148 QSO at IRAM
Molecular surveys

TODAY

PS S J2322+1944, z = 4.12

TOMOROW

ALMA J1148 24 hours

ALMA prediction
CO & H₂ lines for AGN at z ~10

Spaans & Meijerink 2008
H₃⁺ 95µm, HeH⁺ 149µm

100K < T_{gas} < 1000K
Eddington limit for AGN > 10⁶Mₒ
CO from J=15 (170µm)
H₂ S(0) 28µm, S(1) 17µm

5 < z < 20
10²²-10²⁴ cm⁻²
n ~10³-10⁵ cm⁻³
Do SMG actually trace massive haloes?

In the GOODS-N field, cluster of RG and SMG at $z=1.99$

The strongest known association of SMG (Chapman et al 2009)

Overdensity of 10. But only 2 in UV-selected galaxies

⇒ Only a mild overdensity, experiencing brief and strong starburst

Highly active merger periods in modest mass structures

⇒ Merger bias

Herschel and ALMA could probe a large range of environments
SMG in filaments traced by LAE

SSA22
Protocluster region
$z=3.1$

Filament colour
from LAE

SMG 1.1mm from AzTEC on ASTE

$S > 2.7$ mJy
Size $\propto$ flux

Tamura et al 2009
APM08279+5255 z=3.9 lensed QSO

Influence of AGN feedback on CO emission?

This object is one of the brightest in the sky, and has been observed with mm and cm telescopes (amplification factor ~50)
CO(1-0) to CO(11-10) detected
Recent 0.3" resolution CO(1-0) mapping with VLA (Riechers + 2009)

Previously believed to be extended, CO emission is in 2 peaks,
Co-spatial with optical/NIR, may be less amplified than thought (4?)

CO is in a circumnuclear disk of 550 pc radius, inclined by 25°
Mgas ~1.3 \(10^{11}\) Mo \((\Delta V = 556\text{km/s})\)
MBH = 2.3 \(10^{10}\)Mo, bulge 10x less massive than the MBH-\(\sigma\) relation

\(\Rightarrow\) No hint of the influence of the AGN feedback…
APM08279+5255, Riechers et al 09

Magnification revised to 4 (100 before!)
CO co-spatial to optical, close to AGN
MH$_2$ = 1.3 $10^{11}$Mo
QSO at $z=6$

→ An order of magnitude higher MBH than expected

But:

Unknown inclination

Could be a bias in CO width too small due to a detection bias?

→ ALMA will resolve the morphology, and find actual inclinations
Upper limits for LAE $z > 6$

HCM6A, at $z=6.56$ behind the Abell 370 cluster  \( S < 1 \) mJy at 3\( \sigma \)
dust mass < $5.3 \times 10^7$ M\(_\odot\), SFR < 35 M\(_\odot\)/yr. **Boone et al 2007**
No CO detected $M(H_2) < 5 \times 10^9$Mo, if X-factor =0.8 **Wagg et al 2009**

Amplification factor 4.5
+ X factor 4.5 also $\Rightarrow$ 20
$\Rightarrow$ ALMA will have difficulties
Summary of present work

- SMG in continuum

- About 70 systems detected in CO at high z

- May be dominated by selection effects
  - ULIRGs very efficient SFE, compact and highly excited
  - Or more extended gas, with normal SFE and life-times

- Bias of lensing magnification

- Quasars and Starburst intimately linked
  AGN does not quench SF?
Perspective with ALMA

• ALMA deep field in continuum: N(S), SFR (z) and SFH

• the CO lines will be intensively observed at high z with ALMA and determined for « normal » systems

⇒ efficiency of star formation (z), and the kinematics, Mdyn

⇒ If CO not excited, either CII, or go to GBT, EVLA and SKA precursors to detect the low-J CO lines

Galaxies at high z, SFH

⇒ SFH + MH2 ⇒ SFE