ALMA: Molecular gas across cosmic times and environments

Franco-Indian Astronomy school
From Re-ionization to Large Scale Structure
A multiwavelength approach
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Outline

1- Cosmic evolution of gas content

2- Evolution of Star Formation Efficiency

3- Physical processes of quenching

4- Environmental effects
While 6% of baryons are in stars now (Fukugita et al 1998) \( \Omega_\star \sim 3 \times 10^{-3} \)
the atomic gas HI in galaxies is \( \sim 10\% \) (Zwaan et al 2005) \( \Omega_{\text{HI}} \sim 3.5 \times 10^{-4} \)
and the molecular gas, from CO (Sauty et al 2003, Keres et al 2003) \( \Omega_{\text{H}_2} \sim 1.2 \times 10^{-4} \)

The molecular fraction is expected to increase with \( z \):

Galaxy size \( \sim 1/(1+z) \),
+ \( F_{\text{gas}} \) higher:
\( \Rightarrow \) Denser gas \( \text{HI} \rightarrow \text{H}_2 \)

HIZELS, Thomson et al 2017
Cosmic evolution of $\text{H}_2$

*Walter et al, Decarli et al 2014:* Deep PdBI obs of the HDF-N, 3mm

*Decarli et al 2016:* ASPECS, ALMA of UDF in Bands 3 & 6

Evolution more contrasted then in models, factor 3-10

from $M^*$ function and $f_{\text{gas}}$

*Maeda et al 2017*

\[
\rho_{\text{mol}} = \int_{M_{\text{min}}}^{M_{\text{max}}} f_{\text{mol}} M_{\text{star}} \Phi(M_{\text{star}}) dM_{\text{star}}
\]
Why does SFR(z) increases?

The main sequence

SFR

\[ \text{log}(\text{SFR}_{\text{unz}}) = \text{log}(M) \]

\[ \text{log}(\text{SFR}_{\text{unz}}) = \text{log}(M) \]

Gas fraction

Star formation efficiency

- Frequent mergers
- Shorter dynamical times
- Higher gas density

Quenching since \( z = 1.7 \)

Environment
Morphology
Mass

Madau & Dickinson 2014

Whitaker et al 2014

Morphology
Mass
2-Large range of SF efficiency at high-z

In SMGs, starbursts \( t_{\text{dep}} = 1/\text{SFE} \approx 10-100 \text{ Myr} \)

Massive BzK galaxies, CO sizes \( \sim 10 \text{kpc} \)\? \( L(\text{FIR}) \sim 10^{12} \text{ L}_{\odot} \)

« Normal » SFR, \( M(\text{H}_2) \sim 2 \times 10^{10} \text{ M}_{\odot} \) \( t_{\text{dep}} \sim 2 \text{ Gyr} \)

Starburst when gas concentrated in the center (nuclear SB)

Caveat: XCO conversion ratio
Requires high-J CO lines
HCN, HCO+,,,
Dust emission, etc..

High excitation, like MW
\( \Rightarrow \) XCO \( 4.5 \times \) that of ULIRGS
High SFE (starbursts) at $z=1.4-3.2$

Herschel detected starbursts Galaxies from COSMOS, 300-800 Mo/yr, $f_{\text{gas}}$ 30-50%

SFG, $z=3.2$ (COSMOS) 
Schinnerer et al 2017

Starburst
SFR= 10x MS

Silverman et al 2015
EGS1305123 z=1.12

High detection rate >85%, 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, 2013
Resolved Kennicutt-Schmidt diagram

Depletion time smaller than for $z=0$

Freundlich et al. 2013
Scaling relations, several samples

Gas fraction increases regularly with z on the MS

\[ \log(M^*/M_0) = 9.1 - 11.8, \quad z \delta M_S = \text{SFR}/\text{SFR}(\text{MS}) \]

\[ t_{\text{dep}} \sim (1+z)^{-0.57} (\delta M_S)^{-0.44} \]

\[ \mu = \frac{M_{\text{mol}}}{M^*} \sim (1+z)^{2.8} (\delta M_S)^{0.54} (M^*)^{-0.34} \]

Tacconi et al 2017
Depletion time, CO or dust tracers

$T_{\text{dep}}$ large variations quiescent-SB
But slow variation on the MS

Genzel et al 2015
Compilation between $z=0$ and 4

758 galaxies, different samples, normalised to the Main sequence (MS)

PHIBSS2, COLD-GASS (Saintonge et al 2016-17)
ALMA (Decarli et al 2016)
Herschel dust (Magnelli et al 2014, Bethermin et al 2015)

normalised to minimise the zero points of calibration ($M^*$, CO masses..)

$log(M^*/M_0)=9.11.8$, $\delta MS=SFR/SFR(MS)= 10^{-1.3}$ to $10^{2.2}$

$t_{\text{depl}} \sim (1+z)^{-0.57} (\delta MS)^{-0.44}$

$\mu = M_{\text{mol}}/M^* \sim (1+z)^{2.8} (\delta MS)^{0.54} (M^*)^{-0.34}$

Tacconi et al 2017
Normalisation, after z-dependency removed

\[ t_{\text{dep}} \quad M_{\text{mol}}/M^* \]

\[ t_{\text{dep}} \quad \text{fit} \quad M_{\text{mol}}/M^* \quad \text{fit} \]
Depletion time

\[ \log \left( \frac{t_{\text{damp}}}{t_{\text{damp}}(\delta MS)} \right) \]

\[ \log (\delta MS) \]

\[ \log t_{\text{damp}}(\delta MS) \]

\[ \log(\delta R) \]

\[ \log(1+7) \]

\[ \log M^* \]

Normalised optical R

\[ y = -0.44x \]

\[ y = -0.026 + 0.12x \]
Gas fraction $\mu = \frac{M_{\text{mol}}}{M^*}$
SFE and depletion times with continuum

Scoville et al 2016

Scoville et al 2017
sSFR of disks?, slope ~0

Abramson et al 2014

DR4 different SFR estimation
Overestimate in QG
More than B/T, the concentration (Sersic n)

The reason of sSFR/M* slope different from 0
rightarrow High-M galaxies have a much redder bulge
Not for pseudo-bulges!

Z. Pan et al 2016
3- Quenching processes

**FAST (<~0.1 Gyr)**
- Heating the gas (transient)
- Turbulence by interactions, SF feedback
- Gas will dissipate, and SF come back
- Ejecting the gas present (transient)
- SN and AGN winds, radio jets

**SLOW (2-4 Gyr)**
- Stabilising the gas:
- Morphological quenching, bulge formation
- Cutting the gas refueling:
- Gravity/halo quenching, Environment
  (harassment, strangulation, ram-pressure or tidal stripping..)

*Peng et al 2010*
Galactic wind quenching

ALMA obs CO(3-2)
Merger-induced
Starburst: N3256
ULIRG $z=0.01$

High-velocity wings
in both nuclei!
One nearly edge-on, the other face-on

Sakamoto et al 2014
Two bipolar flows, $\tau \sim 1$ Myr

Northern outflow: SF
$V > 750 \text{ km/s}$, 60 $M_\odot$/yr
Wide angle

Southern outflow: AGN
$V \sim 2000 \text{ km/s}$ out to 300 pc
- 50 $M_\odot$/yr
- Highly collimated

Rate comparable to SFR
$\Rightarrow$ efficient quenching?

Sakamoto et al 2014
Molecular outflows

Mrk 231
AGN and also nuclear Starburst, $10^7$-$10^8$ Mo
Outflow 700 Mo/yr

IRAM Ferruglio et al 2010

On kpc scales, $\Rightarrow$ Maiolino et al 2012
affects the galaxy, quenches SF?

Blue wing
Red wing

Cicone et al 2012

\[
\frac{dM}{dt} = 3v \frac{M_{OF}}{R_{OF}} \sim 1000 \text{ Mo/yr}, \quad (5 \times \text{SFR})
\]
Kinetic power $\sim 2 \times 10^{44} \text{ erg/s} \Rightarrow \text{AGN}$

High density, HCN, HCO+, Aalto et al 2012
Relations outflows with AGN

For AGN-hosts, the outflow rate correlates with the AGN power.

\[ \frac{dM}{dt} \sim 20 \frac{L_{\text{AGN}}}{c} \]

Can be explained by energy-driven outflows

*Cicone et al 2014*
Radio mode: molecular flow IC5063

Some of the gas optically thin in the flow?

Morganti et al 2015

Dasyra et al 2016
AGN jet in the plane of N1068

Black V=-50km/s
White V=50km/s

Outflow of 63Mo/yr
About 10 times the SFR in this CMD region

Garcia-Burillo et al 2014
Fueling BH and feedback in low-lum AGN

The smallest outflow detected
AGN feedback
V=100km/s, 7% of the mass
M_{BH} = 4 \times 10^6 M_\odot
Flow momentum = 10 L_{AGN}/c

Combes et al 2013

N1377 precessing jet

Aalto et al 2015
Gas Comes Back!

Multi-phase medium in clusters

Chaotic Cold Accretion (CCA)

Gaspari & Sadowski 2017
Cold gas in filaments

Inflow and outflow coexist

The molecular gas from previous cooling is dragged out by the AGN feedback

The bubbles create inhomogeneities and further cooling
At $R \sim 20 \text{kpc}$, $t_c/t_{ff} \sim 10$
$\Rightarrow$ thermal instability (*McCourt et al 12*)

The cooled gas fuels the AGN

Velocity much lower than free-fall
*Salome et al 2008, 2011*
Trailing wake A1795

Hα

McDonald et al. 2009
60 kpc tail

Salome & Combes 2004

t_{cool} = 300 \text{Myr} = t_{dyn}

Russel et al. 2017

X-rays

bubble
ALMA: cold gas in cool core clusters

Abell 2597 ALMA CO(2-1) absorption in front of the AGN synchrotron

Red-shifted only
Dense clouds fueling the AGN

Tremblay et al 2016
CO absorptions

$10^{21}$-$10^{23}$ cm$^{-2}$ cold ($< 40$K) gas present within 30kpc of the BCG

Only inflowing in CO
Also outflowing in HI

N5044 (David et al 2014)  A2597

Hydra A (Edge et al)
Morphological Quenching (~5 Gyr)

Disks only are more unstable

Bulges and central condensations stabilise disks

Toomre parameter $Q = \frac{\sigma}{\sigma_{\text{crit}}}$

$\sigma_{\text{crit}} = 3.36 \, G \Sigma / \kappa$

Bulge increases $\kappa$, and $Q$
If $\sigma$ and $\Sigma$ remains constant
→ Inside out quenching

Martig et al 2009
Gravity quenching

$M_h > 10^{12} M_\odot$, shocks

$M_h < 10^{12} M_\odot$

Depends on halo mass (not galaxy)
May stop the gas supply
already in groups $\Rightarrow$ red and dead

*Dekel & Birnboim 2005*
4- Environmental effects

- Gas stripped in clusters at $z=0$
- A reversal is expected at $z \sim 1$

*Elbaz et al 2007*

*Chung et al, VIVA with VLA*

The reversal of the star formation-density relation?
Effects of mergers (major or minor)

SF in general enhanced in major mergers

However, suppressed in minor mergers, for the smallest companion

→ Gas heating, stripping at the benefit of the primary

Davies et al 2015 (GAMA) 300 000 galaxies, 20 000 pairs
Both physical processes are acting, difficult to disentangle

NGC 4438 & 4435 in Virgo
First CO detections outside galaxy disks

Vollmer et al 2005
Combes et al 1988
**CO detection in tidal dwarfs and tails**

**Time-scales of the tail formation**

A few 100 Myr

**Time-scale of the bridge**

50-100 Myr

**Aalto et al 2001**

The Medusa

**Time to form H$_2$ clouds and new stars**

Few 10 Myr

**Braine et al 2000**

A105

N2992
Giant Hα tail in Virgo

Kenney+ 2008
Tail around M86: H$_2$ gas in hostile environment

21 CO in red

$10^7$K ICM
Survival during 100 Myr?

MH$_2$ = $2 \times 10^7$Mo
10kpc South of M86

MH$_2$ = $7 \times 10^6$Mo
10kpc NE M86

In situ formation
Or tail from N4438

Dasyra et al 2012
Tidal tail N4388 – M86

At 100kpc distance, 2 \(10^6\) Mo of \(\text{H}_2\)

\[ \text{Formation in situ of H}_2 \]

\[ \text{Star formation enrich the ICM} \]

\[ \text{Low SFE, tdep } \sim 500\text{Gyr} \]

Verdugo et al 2015
Star formation efficiency

Comparison with XUV disks

Gas in tails, and far from disks have not enough pressure from stars

And the gas surface density is not enough for fast HI to H$_2$ transition

Verdugo et al 2015
**Importance of pressure**

The surface density of stars is very important for the SF efficiency.

H$_2$/HI

The HI to H$_2$ transition is favored by external pressure.

*Shi, Helou et al 2011*

*Blitz & Rosolowsky 2006*
Ram-pressure in Norma cluster

Ram pressure in clusters: in general slow:
In Virgo, HI deficient, but not $H_2$ (Kenney & Young 1989)
but can be fast in exceptional cases: ESO137-001

Jachym et al 2014
Ram-pressure quenching

Tail of 80kpc in X-ray gas,
40kpc in CO
$M(H_2)$ in C = 1.5 $10^8$Mo

Jachym et al 2014
Ram-pressure in Coma

D100 tail: thinner
Last stage of stripping
CO detected along, until 45kpc

Jachym et al 2016
Molecular gas in the shell

$\text{H}_2$ dominant at E, while HI at W

H\(\alpha\) map

Red: CO, White: HI, FUV-Galex: black, CO\(21\), HI contours

Salome et al 2016
Star formation triggering

The radio jet effectively triggers star formation in the shell along the jet $\Rightarrow$ positive AGN feedback

However, the SF efficiency is lower than in disks

$\Rightarrow$ Not enough pressure

$\Rightarrow$ $T_{\text{dep}}$ larger than a Hubble time

Salome et al 2016
Role of mergers in starbursts

At low z, mergers trigger starbursts – The most energetic ULIRGs with highest SFE are all mergers (Sanders & Mirabel 1996)

Mergers increase $\sim(1+z)^4$ (Lefevre et al, 2000, Lotz et al 2011)

$\Rightarrow$ How SFE varies with z?

Due to high gas fraction, the number of clumps, violent instabilities, is already large in isolated galaxies at high z

Fensch et al 2017
Gas density PDF

No difference in the PDF for high gas fraction for isolated or interacting galaxies \textit{(Fensch et al. 2017)}

Density threshold for star formation: 30 and $10^5$ cm$^{-3}$

![Graphs showing density PDF for different gas fractions and timescales.](image)

F$_{\text{gas}} = 10\%$

F$_{\text{gas}} = 60\%$

to have SFR = 1Mo/yr and 60Mo/yr for isolated galaxies
Galaxy mergers with high gas content

Perret et al 2014

\[ T = 640 \text{ Myr} \]

No SFR difference with isolated case

However: numerical effects?
(temperature floor, depends on density)
Starbursts at high redshift \( z \sim 2-3 \)

- Eddington limit
  \( t_{\text{dep}} = 20 \text{Myr} \)

- MS, \( z=0 \) (\( t_{\text{dep}} = 2 \text{Gyr} \))

Dust opacities
\( \kappa = 10, 30 \text{ cm}^2/\text{g} \)

Andrews & Thompson 2011

Canameras et al 2016
Conclusion

Galaxies at high z have a larger gas fraction
Whatever their position, on the MS or not

SFE vs z, small evolution on MS, larger for SB
Depletion time 2 or 10 times smaller

The starburst is triggered when the gas is concentrated (merger?)
Diagnostics with CO excitation, Dense gas tracers (HCN, HCO+)

Simulations show SF saturation at high z
No influence of galaxy interactions, contrary to observations