Molecular Gas at High Redshift

Fabian Walter (MPIA)

w/

Bertoldi, Carilli, Daddi, Da Cunha, Decarli, Hodge, Maiolino, Riechers, Sargent, Venemans, Wagg, Wang, Weiss
Galaxy growth through gas accretion...

...but this gas supply is currently largely unconstrained observationally.
Deep fields: 100s hours, <1 sqdeg, mostly done in optical/NIR

→ this plot shows the consequence of gas supply in galaxies

Research in last decade - Cosmic Evolution of the cosmic star formation rate density

\[ \Omega_{\text{SFR}} \left[ \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-3} \right] \]
Research in last decade - Cosmic Evolution of the cosmic star formation rate density

Deep fields: 100s hours, <1 sqdeg, mostly done in optical/NIR

→ this plot shows the consequence of gas supply in galaxies

perhaps the more fundamental plot would be:

how do we get there?
A typical dusty high-redshift SED
CO transitions as function of redshift, $f(T, \rho)$
CO transitions as function of redshift, $f(T, \rho)$

significant coverage in frequency space
CO transitions as function of redshift, $f(T, \rho)$

- PdBI/ALMA 3mm band
- PdBI 2mm band
- PdBI/ALMA 1mm band
- PdBI/ALMA submm band
- EVLA K, K', Q band

significant coverage in frequency space

at high redshift: can only detect high-J CO transitions

non-trivial to derive molecular gas masses, even if conversion factor $L_{\text{CO}(1-0)} \rightarrow \text{H}_2$ mass was known
CO transitions as function of redshift, \( f(T, \rho) \)

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>PdBI/ALMA 3mm band</th>
<th>PdBI 2mm band</th>
<th>PdBI/ALMA 1mm band</th>
<th>PdBI/ALMA submm band</th>
<th>EVLA K, K(_a), Q band</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<td>&lt;10% ALMA sensitivity</td>
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</table>

**practical issues**

Significant coverage in frequency space

At high redshift: can only detect high-J CO transitions

Non-trivial to derive molecular gas masses, even if conversion factor \( L_{CO(1-0)} \rightarrow H_2 \) mass was known

Once CO is detected:

- **Brightness** \( \rightarrow M_{gas} \) (fuel for SF, evol. state, \( t_{dep} \))
- **Excitation** \( \rightarrow n_{gas}, T_{kin} \) (phys. conditions for SF)
- **Imaging** \( \rightarrow \Sigma_{gas}, M_{dyn} \) (sys. potential \( \rightarrow M_{tot} \))
- CO is best (but by no means perfect) tracer for molecular gas, H$_2$

so far: individual studies, mostly
QSO: host galaxies of accreting Black Holes
SMGs: highly SF galaxies

\[ \text{SFR} \geq 1000 \, \text{M}_\odot \, \text{yr}^{-1} \]
- CO is best (but by no means perfect) tracer for molecular gas, H$_2$

so far: individual studies, mostly
QSO: host galaxies of accreting Black Holes
SMGs: highly SF galaxies

detection limit: $\sim 10^{10-11}$ M$_{\odot}$
CO now ‘routinely’ detected in z=6 QSOs.

z=6: age of universe less than 1 Gyr.
presence of CO(6-5) implies major enrichment in quasar host galaxies
CO emission can be spatially resolved

Bright z=4 submillimeter galaxy GN20

1kpc resolution at z=4!

Reveals clumpy rotating molecular gas disk: evidence for cold mode accretion?

but: expensive.... ~100 hours with JVLA

Hodge et al. 2012
Other tracers: Atomic Carbon (Cl)

CI(2-1)[809GHz] and CI(1-0)[492GHz]

independent constraints on $T_{ex}$ needed for LVG modeling
Other tracers at high density

\[ HCO^+ + 1-0 \]

- \( n_{\text{cr}} > 1 \times 10^5 \text{ cm}^{-3} \) - 100x denser than CO, \( \sim \) GMC cores
- Dense gas lines 10-30x less luminous than CO
- Line ratios similar to local ULIRGs, e.g., Arp 220

\[ \Rightarrow \text{No significant ‘chemical evolution’ of mol. ISM?} \]

\[ HCN 1-0 \]

\[ HCO^+ 1-0 \]

\[ CN (N=3-2) \]

\[ CS 3-2 \]

\[ z=2.6 \]

\[ z=4 \]

Solomon ea. 2003
Riechers ea., 2007a, 2009
Garcia-Burillo ea 2008
CO ladder -- tedious observations...(128,127),(897,869)

IRAM 30m CO SED survey
(1, 2, 3mm bands)

Weiss et al. 2013
Lensing helps

The Eyelash

Swinbank et al. 2011, Danielson et al. 2011
Low-J observations in the cm regime: need large collecting area.
z>2-4 SMGs show complex, extended, low-excitation gas reservoirs typically 10kpc, with FIR continuum sizes of 2-4kpc (starburst regions)

Riechers et al. 2011, Ivison et al. 2011

THE ASTROPHYSICAL JOURNAL LETTERS (EVLA SPECIAL ISSUE)
CO excitation: putting it all together:

Weiss et al. 2013
$T_{\text{kin}} \sim 200 \text{ K } (T_{\text{dust}} \sim 200 \text{ K})$

$n(H_2) \sim 10^{4.2} \text{ cm}^{-3}$

Strongly lensed (m=80-100) central ~200pc surrounding the QSO AGN heating!

$T_{\text{kin}} \sim 40 - 60 \text{ K } (T_{\text{dust}} \sim 50 \text{ K})$

$n(H_2) \sim 10^{3.6-4.3} \text{ cm}^{-3}$

$T_{\text{kin}} \sim 30-50 \text{ K } (T_{\text{dust}} \sim 30-50 \text{ K})$

$n(H_2) \sim 10^{2.7-3.5} \text{ cm}^{-3}$

Weiss et al. 2013
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Strongly lensed (m=80-100) central $\sim200$pc
surrounding the QSO. AGN heating!

Kin $\sim 30-50$ K ($T_{\text{dust}} \sim 30-50$ K)
$n(H_2) \sim 10^{2.7-3.5}$ cm$^{-3}$

Weiss et al. 2013
FIR vs. CO luminosity

N = 1.4

Riechers et al.
Kennicutt's 98 data

N = 1.4

high-z Quasars/submillimeter galaxies

Riechers et al.
optical/NIR selected galaxies (BzK), SFR few 100 $M_{\odot}$ yr$^{-1}$ are very rich in molecular gas

Molecular conversion factor: Galactic
gas fractions: $f_{\text{gas}} = 0.5$-0.7

Daddi et al 2008/2010, Tacconi 2010

Dannerbauer et al. 2009
Location of BzK galaxies in ‘SF law’ plot

- BzKS have significantly less $L_{IR}$ for given $L_{CO}$

Daddi et al. 2010
Location of BzK galaxies in ‘SF law’ plot

- BzKs have significantly less $L_{\text{IR}}$ for given $L_{\text{CO}}$

Daddi et al. 2010

note: this plot: observables only
Going from luminosities to masses

Two sequences:
- disks
- starbursts

FIR luminosity ($\sim$SFR) vs. gas mass ($M_{\text{H}_2}$)

$N=1.3$

Daddi et al. 2010
Genzel et al. 2010
Star Formation Efficiencies a.k.a. Depletion Times

immediate implication:

gas depletion times long for BzKs (sim. to spirals)

Daddi et al. 2010
Relation between gas and star formation is complex.

High redshift gas supply

Daddi, et al., 2010, Genzel et al. 2010

Log (molecular gas surface density) vs. Log (SFR surface density)

Graph showing data points that represent high-z galaxies and local galaxies.
high redshift gas supply

relation between gas and star formation is complex

$\Omega(SFR) \ [M_{\odot} \ yr^{-1} \ Mpc^{-3}]$

$\Omega(mol) \ [M_{\odot} \ Mpc^{-3}]$

→ not trivial to predict $\Omega(M_{mol})$ from $\Omega(SFR)$
[talk by Mark Sargent]

solution: unbiased census of molecular gas, the fuel for star formation
i.e. a molecular deep field (at the same time: continuum deep field)
CO transitions as function of redshift, $f(T, \rho)$

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Frequency [GHz]</th>
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<tr>
<td>9</td>
<td>275</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
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</tbody>
</table>

PdBI/ALMA submm band
PdBI/ALMA 1mm band
PdBI 2mm band
PdBI/ALMA 3mm band

$\leq 10\%$ ALMA sensitivity
EVLA K,K_a,Q band

this is now possible given wide bandwidths of current and upcoming facilities

ALMA deep field: expect 100s of detections

Hubble UDF
ALMA simulations
da Cunha et al. submitted
**continuum:** observed UV/optical SEDs → SED models (Da Cunha) → dust luminosity (from attenuation in UV) → FIR luminosity → ALMA flux densities

**lines:** $L_{\text{FIR}} \rightarrow L_{\text{CO}}$ (Daddi et al., Genzel et al.), assuming range of CO excitations $\text{MW} \leftrightarrow \text{M82}$

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**Stellar mass**

**Star formation rate**

**Dust luminosity**

Whole sample (13,099 galaxies)

- $0.0 \leq z < 1.5$ (5,660 galaxies)
- $1.5 \leq z < 2.5$ (4,286 galaxies)
- $2.5 \leq z < 5.0$ (3,153 galaxies)
predicted properties of UDF galaxies: example: band 6 continuum

- Full ALMA
- total ~300 hours
- FOV = 26 arcsec
- 6.2 hours/pointing
- rms = 5.1 microJy
- >600 detections

actual observations can be immediately compared to these expectations!
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observed CO luminosities: comparisons to models

e.g. comparison to Obreschkow et al. Lagos et al., Sargent et al.

actual observations can be immediately compared to these expectations!

talk by Mark Sargent

Sargent et al. 2012
predictions by numerical simulations

AREPO (Springel et al., Vogelsberger et al.): distribution of molecular gas at $z \sim 1, 2$ and $3$

size: $1' \times 1'$ ~ ALMA band 3 primary beam size

can immediately compare observations to simulations
first molecular deep field with PdBI: HDF

covered full 3mm band in 10 frequency settings (2011-2012)
3mm band: low-J coverage, highest fractional BW, largest PB

almost complete redshift coverage
first molecular deep field with PdBI: HDF

covered full 3mm band in 10 frequency settings (2011-2012)
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almost complete redshift coverage

Hughes et al. 1998

this field included HDF850.1
The Case of HDF850.1

spectrum at position of HDF850.1
The Case of HDF850.1

spectrum at position of HDF850.1
The Case of HDF850.1

spectrum at position of HDF850.1

This nails the redshift to $z=5.183$!

Walter et al. 2012
The Case of HDF850.1

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Walter et al. 2012
The Case of HDF850.1

spectra at position of HDF850.1

This nails the redshift to $z=5.183$!

Walter et al. 2012

precise location and redshift: no counterpart identifiable in deepest HST observations

HDF850.1 [CII] contours on I-band
red/blue–shifted [CII] on J-band

however source is located in galaxy overdensity at $z=5.2$, including one quasar!
blind detection of other sources:

example:

2nd CO line confirms $z=1.76$
blind detection of other sources:

example:

volume probed for CO(2-1) line from $z=1.0$-$1.8$ ($<z>=1.4$)

first blind constraints on $\Omega (M_{\text{mol}})$

2nd CO line confirms $z=1.76$
going to the highest redshifts, $z > > 5$

will we lose CO as our main tracer?

problem I: conversion factor at low metallicities?

problem II: the CMB is not our friend

$T_{ex} = 18$ K

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\end{figure}

da Cunha et al. 2012
will we loose CO as our main tracer?

problem I: conversion factor at low metallicities?
problem II: the CMB is not our friend

going to the highest redshifts, $z \gg 5$

da Cunha et al. 2012
CO line redshift coverage for ALMA and JVLA

**ALMA**
- Band 10 (787-950 GHz)
- Band 9 (602-720 GHz)
- Band 8 (385-500 GHz)
- Band 7 (275-370 GHz)
- Band 6 (211-275 GHz)
- Band 4 (125-163 GHz)
- Band 3 (84-119 GHz)

**EVLA**
- Q 0.7cm (40-50 GHz)
- Ka 1.0cm (26-40 GHz)
- K 1.3cm (18-26 GHz)

![Graph showing CO line redshift coverage for ALMA and JVLA](image-url)
CO line redshift coverage for ALMA and JVLA
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EVLA
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going to the highest redshifts
[CII] to the rescue?

- [CII] is bright
- [CII] is not easily interpretable, traces ionized and neutral gas

May be easier to detect fainter, low metallicity sources?

Maiolino et al. 2009 [updated]
Local [CII] calibrations ongoing...

e.g., KINGFISH project
(Smith et al., Bolatto et al.)
• [CII] size ~ 1.5 kpc => SFR/area ~ 1000 M_☉ yr⁻¹ kpc⁻²

• Maximal starburst: (Thompson et al. 2005)
  - Self-gravitating gas disk, Vertical support: radiation pressure
quick poll!

SFRSD = 1000 M$_{\text{sun}}$ yr$^{-1}$ kpc$^{-2}$ !?!

Comparison to star formation rate surface density in Orion?!

SFRSD$_{\text{J148}}$ = 1000 M$_{\text{sun}}$ yr$^{-1}$ kpc$^{-2}$

A) SFRSD$_{\text{Orion}}$ = 10$^{-6}$ × SFRSD$_{\text{J148}}$
B) = 10$^{-3}$ × SFRSD$_{\text{J148}}$
C) = 1 × SFRSD$_{\text{J148}}$
**quick poll!**

SFRSD = 1000 $M_{\text{sun}}$ yr$^{-1}$ kpc$^{-2}$ !??

Comparison to star formation rate surface density in Orion??

SFRSD$_{J1148}$ = 1000 $M_{\text{sun}}$ yr$^{-1}$ kpc$^{-2}$

- **A)** SFRSD$_{\text{Orion}}$ = $10^{-6}$ x SFRSD$_{J1148}$
- **B)** = $10^{-3}$ x SFRSD$_{J1148}$
- **C)** = 1 x SFRSD$_{J1148}$
Comparison to star formation rate surface density in Orion??

\[ SFRSD_{\text{Orion}} = 10^{-6} \times SFRSD_{J148} \]

\[ SFRSD_{\text{Orion}} = 10^{-3} \times SFRSD_{J148} \]

\[ SFRSD_{\text{Orion}} = 1 \times SFRSD_{J148} \]

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RADIATION PRESSURE-SUPPORTED STARBURST DISKS AND ACTIVE GALACTIC NUCLEUS FUELING
TODD A. THOMPSON,1,2 ELIEQ KAMACET,3 AND NORMAN MURRAY4,5,6
Accepted 2005 March 1, accepted 2005 May 14

ABSTRACT

We consider the structure of marginally Toomre-stable starburst disks under the assumption that radiation pressure on dust grains provides the dominant vertical support against gravity. This assumption is particularly appropriate when the disk is optically thick to its own infrared radiation, as in the central regions of ULIRGs. We argue that because the disk radiates at its Eddington limit (for dust), the “Schmidt law” for star formation changes in the optically thick limit, with the star formation rate per unit area scaling as \( \Sigma_* \propto \Sigma_g / \kappa \), where \( \Sigma_g \) is the gas surface density and \( \kappa \) is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of \( F \sim 10^{13} L_\odot \text{ kpc}^{-2}, \Sigma_* \sim 10^4 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}, \) and \( T_{\text{eff}} \sim 90 \text{ K} \), respectively. We compare our model predictions with observations of ULIRGs and find good agreement. We extend our model of starburst disks from many hundred parsecs scales to subparsec density and \( \kappa \) is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of \( F \sim 10^{13} L_\odot \text{ kpc}^{-2}, \Sigma_* \sim 10^4 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}, \) and \( T_{\text{eff}} \sim 90 \text{ K} \), respectively. We compare our model predictions with observations of ULIRGs

2 AGNs. We also argue that the disk of young stars in the Galactic center may be the remnant of such a compact nuclear starburst.
Small survey at PdBI to detect [CII] at z>6.5: unsuccessful

Search for [CII] in z>6.5 Lyman Alpha Emitters (and one z~8 GRB host)
[CII] now detected out to z=7.1(!)

Only one quasar known at z>7 (Mortlock et al. 2011)

Bright detection in [CII] -- source visible from ALMA

Venemans et al. 2012
BRI 1202: [CII]

ALMA: An SMG-Quasar pair at z=4.7

Wagg et al. 2012
Carilli et al. 2012

dramatic S/N in 0.5 hours w/ 16 antennae
ALMA always covers 8GHz of bandwidth -- we looked at ~100 SMGs in ECDFS

Two show evidence for line emission - most likely [CII] at z~4.4

Swinbank et al. 2013
[NII] as a tracer of ionized medium at high redshift

[NII] in strongly lensed source at z=4 (MM18423) (Lestrade et al. 2010)

resolved star formation law at high redshift!

Decarli, FW et al. 2012
- **the future is now**

- CO remains best direct tracer of molecular gas mass at intermediate $z$

- excitation critical to derive masses etc.

- may lose CO at highest redshifts (CMB)...
  \[ \rightarrow \] fine structure lines

- so far: all detections in systems w/ SFR > 100 M$_{\odot}$ yr$^{-1}$

- soon: unbiased blind deep fields with ALMA

- ultimate goal: constraints on $\Omega_{\text{CO}}(z)$ and thus $\sim \Omega_{\text{mol}}(z)$
THE END