Molecular gas in galaxies, now and in the past

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Large spectroscopic surveys - stars, atomic gas and molecular gas
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ALFALFA

SDSS
Large spectroscopic surveys - stars, atomic gas and molecular gas

- xCOLD GASS
- ALFALFA
- SDSS
Large spectroscopic surveys - stars, atomic gas and molecular gas

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- SDSS
mid 1990s: Observations and theory suggest galaxy evolution is merger-driven

Deep HST field observations reveal:
- a population of high-redshift compact blue galaxies
- a significant number of distant galaxies with irregular morphologies.
- the redshift evolution of the SFR density in the Universe

In the local Universe, galaxies with such high SFRs are major mergers, so…
early 2000s: near-IR integral field spectroscopy revels that the clumpy, highly star-forming distant galaxies are in fact kinematically normal rotating discs.
Sensitive instrumentation finally allows for the detection of CO in high-redshift normal galaxies. Galaxies at high-z have large gas mass fraction, naturally explaining their very large SFRs.

See also Daddi et al. (2010)
The current observational picture

**the star formation “main sequence”**
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)

$$\text{SFR} \sim M^a(1+z)^b, \text{ where } a \sim 0.8, b \sim 2.5$$

- Galaxies on the main sequence (MS) contribute ~90% of the star formation.
- Duty cycles on the MS are high at 40-70%
  implying that “catastrophic” events like **major mergers** cannot be the main agent responsible for regulating star formation.
Star formation and the baryon cycle

Tumlinson, Peeples and Werk (2017)
direct molecular gas measurements for large, representative samples of normal star forming galaxies from both IRAM facilities

**xCOLD GASS**

Pls A. Saintonge (UCL), B. Catinella (UWA), G. Kauffmann (MPA), C. Kramer (IRAM)

950h IRAM 30-m Large Programmes
+1500h Arecibo Programme for HI

532 SDSS-selected galaxies with 0.01<z<0.05, M*>10^9

see e.g. Saintonge et al. 2011a, 2017

**PHIBSS**

Pls L. Tacconi, R. Genzel (MPE), F. Combes (Paris)

500h IRAM PdBI Large Programmes

150 star forming galaxies with 1.0<z<2.5, 3x10^{10}<M^*<3x10^{11}
+ high-resolution follow-up


**Lensed galaxies**

Pl D. Lutz (MPE), A. Baker (Rutgers)

IRAM PdBI

17 lensed star forming galaxies with 1.5<z<3.1, M*>10^9
includes full Herschel PACS+SPIRE photometry

see Saintonge et al. 2013

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**xCOLD GASS + PHIBSS: IRAM legacy surveys for galaxy evolution studies**
The position of a galaxy in the SFR-M* plane depends on:

(1) how much fuel it has
(2) how much of it is available for star formation
(3) the efficiency of the conversion of this gas into stars

Saintonge et al. (2017)
Cold gas in the SFR-M* plane

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Saintonge et al. (2017)
Cold gas in the SFR-M* plane

Saintonge et al. (2012)

**BOTH** $\text{H}_2$ contents and star formation efficiency vary *across* the MS
as galaxies evolve along the main sequence, they steadily consume their gas supply
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Redshift independence of gas scaling relations

Tacconi et al. (2013)
The redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale. This observation is in strong support of the equilibrium model for galaxy evolution.
Combined dust and gas scaling relations

taking out zero-point offset

Tacconi, Genzel, Saintonge et al. (2018)
Star formation and the baryon cycle

Tumlinson, Peeples and Werk (2017)
Studying the star formation relation on multiple scales

<500 pc scales

~kpc scales

global scales

Schruba et al. (2010)

Bigiel et al. (2011)

Genzel et al. (2010)
Studying the star formation relation on multiple scales

Koda et al. (2009)
Studying the star formation relation on multiple scales
Some important questions:

- Do the properties of the GMC population of a galaxy depend on its global properties?
- How does the environment influence the formation of GMCs?
- Once GMCs are formed, does star formation occur with the same efficiency in all environments?
GMC properties depend on global galaxy properties!

ALMA/NOEMA studies of the GMCs in a range of nearby galaxies:

![Images from A. Hughes](Images from A. Hughes)

shape of GMC mass distribution is not universal: slope and turnover mass increase in more massive systems

Images from A. Hughes
PHANGS: ALMA+VLT/MUSE survey for star formation in an extragalactic context

Credit: PHANGS, ALMA (PI: A. Leroy), HST/STScI (PI: Smartt)

ALMA Large Programme: 1'' imaging in CO(2-1) of ~60 nearby disc galaxies (PI: E. Schinnerer)
+ associated programmes with VLA, VLT/MUSE, IRAM/NOEMA
PHANGS: ALMA+VLT/MUSE survey for star formation in an extragalactic context

(slide from A. Schruba at "The Laws of Star Formation", Cambridge, July 2018)
Comparing the mass-weighted average state of the gas at high physical resolution and correlate it with the balance between star formation and gas observed on larger scales (capturing time-averaged cycling).

\[
\frac{\text{SFR}}{M_{\text{gas}}} = t_{\text{dep}}
\]

\[
\frac{\text{SFR}}{M_{\text{gas}}} = \frac{\epsilon_{\text{ff}}}{t_{\text{ff}}}
\]

Figure: Utomo, Schruba & Phangs 18 (on arXiv today)
Comparing the mass-weighted average state of the gas at high physical resolution and correlate it with the balance between star formation and gas observed on larger scales (capturing time-averaged cycling).

\[ SFR = \varepsilon_{ff} \frac{M_{\text{gas}}}{t_{ff}} \text{ with } t_{ff} \sim (\Sigma/h)^{-0.5} \]
EMIR Multi-line Probe of the ISM
Regulating Galaxy Evolution

PI: F. Bigiel, IRAM-30m Large Program
(−600 h), observations 2014-2017

• Full galaxy maps of:
  ✓ Dense gas tracers: HCN, HCO+, HNC
  ✓ CO isotop. $^{13}$CO, C$^{18}$O + new $^{12}$CO(1-0)
  ✓ Opportunity: N$_2$H$^+$, HNCO, C$_2$H, SiO

• 9 nearby (∼10Mpc) disk galaxies

• Resolution ∼ 1-2 kpc

Papers: Usero+15, Bigiel+16, Jimenez-Donaire+17a,b, Leroy+17, Gallagher+18,
Cormier+18, Jimenez-Donaire+(in prep.),
Chatzigiannakis+(in prep.)

The EMPIRE Team
F. Bigiel, M.J. Jimenez-Donaire, A. Leroy, D. Cormier, A.
Usero, M. Gallagher, J. Puschnig, D. Chatzigiannakis,
A. Bolatto, S. Garcia-Burillo, A. Hughes, A. Kepley, C.
Kramer, J. Pety, K. Sandstrom, E. Schinnerer, A.
Schruba, K. Schuster, F. Walter, L. Zschaechner
Efficiency of dense gas to form stars seems to drop towards galaxy center, high stellar surface densities, high pressure regions and high molecular gas fractions!

The EMPIRE Survey. Jiménez-Donaire et al. (in prep.); Gallagher+18, Bigiel+16, Usero+15
This appears to lead to a context-dependent role for the gas that emits in HCN and similar lines, evidenced by the changing IR-to-line ratios with environment.
Technical challenge: How do we move forward and explore low mass and/or high redshift galaxies?

An example of very high redshift molecular gas work:

Lensed z=8.3 galaxy observed with ALMA (Laporte et al. 2017)

Analysis of the available photometric data and the modest gravitational magnification ($\mu \sim 2$) indicates A2744_YD4 has a stellar mass of $\sim 2 \times 10^9 \, M_\odot$, a star formation rate of $\sim 20 \, M_\odot/yr$ and a dust mass of $\sim 6 \times 10^6 \, M_\odot$. We discuss the implications of the formation of such a dust mass only $\sim 200$ Myr after the onset of cosmic reionisation.
Technical challenge: How do we move forward and explore low mass and/or high redshift galaxies?

Technical challenge: How do we increase the accuracy of molecular gas measurements?

the [CII]/CO ratio should track variations in the level of photodissociation of CO, and therefore give us a handle on $X_{CO}$

example galaxy: Herschel/PACS and IRAM-30m
Where does [CII] emission come from?

Bayesian information criterion used to determine the parameters required to predict the [CII] “molecular fraction”

Key parameters:
- metallicity
- density
- dust mass fraction
- SSFR

In nearby galaxies, 50-85% of the [CII] emission comes from molecular regions.

Accurso et al. (2016a)
Dust as a probe of the cold ISM

An alternative approach to CO line observations:

FIR/submm continuum observations → dust mass measurements → gas mass estimations

\[ M_{\text{gas}} = M_{\text{dust}} \times \text{GDR} \]

Metallicity (12+logO/H)

Leroy et al. (2011)
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Metallicity (12+logO/H) = GDR

M_{gas} = M_{dust} \times GDR

Example SED Fit to Galaxy UGC02369

Casey (2012)

Leroy et al. (2011)

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Metallicity (12+logO/H)

Casey (2012)

\[ M_{\text{gas}} = M_{\text{dust}} \times \text{GDR} \]

H-ATLAS

\[ M_{\text{gas}} = M_{\text{H}_2} + M_{\text{HI}} \]

Saintonge et al. (2013)
Detailed studies of the cold ISM contain info about the entire galactic ecosystem, allow to sample large parameter space, and provide strong constraints for models.

PHANGS
High resolution ALMA imaging of a statistical sample
PI E. Schinnerer + A. Leroy

JINGLE
New JCMT legacy survey for dust+gas in nearby galaxy
Pls A. Saintonge (UCL), C. Wilson (McMaster), T. Xiao (SHAO)

PHIBSS2
Quadrupling the PHIBSS sample and extending to lower/higher masses, lower/higher redshift...
Pls L. Tacconi (MPE), F. Combes (Paris), R. Neri (IRAM), S. Garcia-Burillo (Madrid)
1700h IRAM PdBI Legacy Programme
~200 star forming galaxies with 0.5<z<2.5, 10^{10}<M^*<5x10^{11}

ALMA?
Yes, for high-res follow-up and z>2.5, but must first understand the systematics in low metallicity environments
+ connect global properties to physics of star formation on sub-kpc to cloud scales!

Conclusions and outlook
Where does [CII] emission come from?

Not all [CII] emission comes from the PDR region! → new radiative transfer **multi-phase ISM model** combining STARBURST99 (stellar radiation field), MOCCASIN (ionised region) and 3D-PDR (PDR and diffuse neutral medium)

Accurso et al. (2016a)
Using the [CII]/CO ratio to derive a new conversion function

[CII]/CO correlates particularly strongly with quantities that describe either the dust content or the strength of the radiation field.

Accurso et al. (2016b)