The gas in galaxies and how it is affected by environment

Gregory Rudnick (University of Kansas)
Why should we care about gas?

From the days when HI was king

Star formation suppression means gas removal/consumption

\[
\log \Sigma_{SFR} \left(M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}\right) = \alpha + \beta \log \Sigma_{gas} \left(M_{\odot} \text{pc}^{-2}\right)
\]

Kennicutt 1998

Gregory Rudnick - University of Kansas
### ISM is inherently multi-phase

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<td>10(^7)–10(^8)</td>
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Sparke and Gallagher

H-alpha
ISM is inherently multi-phase

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• HI is optically thin so you see all the gas
ISM is inherently multi-phase

- **Our imperfect window to molecular gas contents**

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Sparke and Gallagher
Molecular gas contents derived through CO

For Milky Way
\[ \alpha_{CO} = 4.4 \, M_{\text{sol}} \, \text{pc}^{-2} \, (K \, \text{km s}^{-1}) \]

For ULIRGS
\[ \alpha_{CO} = 1.0 \, M_{\text{sol}} \, \text{pc}^{-2} \, (K \, \text{km s}^{-1}) \]

\( \alpha_{CO} \) depends on gas metallicity

\[ M(H_2) = \alpha_{CO} L'_{CO} \]
Molecular gas is hard to measure but worth it

- SF is best correlated with molecular gas
- Molecular gas is consumed with constant efficiency and constant gas consumption timescale $\sim 2.3$ Gyr (Bigiel et al. 2011)

![Gas surface density at which HI saturates](image)

Krumholz+08,09

Bigiel+ 2008
Definitions

Boselli et al. 2006

…the definition of starvation that we adopt here is the consumption of the gas via star formation when the cosmological infall of “pristine” gas is stopped…

Many others, e.g. Peng+15, McGee talk

ram pressure stripping is the stripping of any gas belonging to the galaxy via interaction with the intra cluster or group medium.

In this definition Larson et al. (1980) process is a kind of ram pressure stripping

We need to say what kind of gas is being stripped: HI, ionized gas, H$_2$, dense molecular gas
HI stripping

- HI can be stripped from outskirts and compressed along infall direction

- Seen also in simulations

- HI deficiency measured as offset from HI vs. $R_{\text{opt}}$ relation.
In Herschel reference survey (HRS)

- 92% of HI normal galaxies lie outside of Virgo
- 78% HI-deficient galaxies lie in Virgo or associated substructures
- Cluster has lower HI mass fraction
In Herschel reference survey (HRS)
• HI deficiency already found at group halo masses.
This is all great, but what does HI stripping/consumption tell us about star formation quenching?

Need to pursue molecular gas.
Case studies for Molecular gas stripping

x-ray
Halpha

Jachym+2014
Case studies for Molecular gas stripping

Scott+15
HI normal
moderately HI deficient
very HI deficient

In Herschel reference survey (HRS)

- HI deficient galaxies also deficient in $H_2$
- HI more easily stripped than CO at all most radii in galaxy
HI and H$_2$ galaxies are in the green valley

- Gas consumption timescale ~2-3 times stripping timescale
  - stripping more relevant for gas depletion
  - But outflows will shorten gas consumption timescales and negates this argument.

Boselli+14

H$_2$ deficient galaxies miss highest SSFR
Not all molecular gas is created equal

- At same $L_{\text{IR}}$, clusters have lower $L_{\text{CO}}$

- Interpretation: diffuse CO is stripped but dense CO remains
Not all molecular gas is created equal

- $^{13}$CO is optically thin and traces denser gas
- Denser environments have more dense gas
- Interpretation:
  - enhanced $^{13}$CO from mass loss
  - enhanced pressure from ICM
  - stripping of diffuse gas

Field ETG
Spirals
Virgo ETGs

Alatalo+13
Only the dense gas remains

Kenney+15
Magnetic confinement of dense gas

- Magnetic fields can help to retain densest gas
Gas in the most distant cluster galaxies

Rudnick+ in prep

- Deepest ever JVLA image taken in CO. 45h on source analyzed with 60h more in hand.

JVLA field of view

CO detection
spec member
• Most galaxies form stars on a “main sequence” of SFR and $M_{\text{star}}$

• CO-detected galaxies are on/below main sequence
• galaxies are among the most massive

• galaxies are among the most gas rich

• $M_{\text{gas}} / (M_{\text{gas}} + M_{\text{star}}) = 0.6-0.7$

• $M_{\text{gas}}/M_{\text{star}} = 1.5-2.5$

Rudnick+ in prep
• CO over-luminous compared to SFR selected galaxies

• What is preventing the CO from forming stars?
  • Are the physical conditions of the gas different?
  • Is the stability of gas different?
  • Is environment playing a role?

Rudnick+ in prep
• All blind CO detected sources at z>1 are extremely compact

• Compact mass distribution can stabilize gas (Saintonge+12)

• This cluster is merger rich (Lotz+12; Rudnick+12)
  • Minor mergers may prevent gas from cooling

Rudnick+ in prep
• Field galaxies have ~0.7 Gyr gas consumption timescales and require replenishment. (Daddi et al. 2008; Aravena et al. 2010; Tacconi et al. 2010; Tacconi et al. 2013)

• Cluster galaxies have long gas consumption timescales (1-4Gyr), assuming constant SFR.

• 80% of $10^{11}$ $M_{\odot}$ galaxies in $z\sim1$ clusters are passive.

• No additional gas accretion is allowed over 2 Gyr to $z\sim1$

• Potential sign of high-z environmental truncation of gas accretion

Rudnick+ in prep
Summary

• All gas phases experience depletion in dense environments
• Molecular gas is depleted less
• Dense molecular gas less so
• Gas deficient galaxies have suppressed star formation
• High-z studies may reveal cutoff in gas accretion and inefficient star formation

Future needs

• Probe dense gas directly - only at low-z
• Study gas at larger range of environmental densities
• Spatially resolve gas with NOEMA + ALMA
• Probe to higher redshift to
  • see when gas stripping becomes important
  • catch death of massive galaxies

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