Gas accretion and star formation: drivers of galaxy evolution

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The old picture: merger-driven galaxy evolution

from mid-80s to 5-10 years ago: merging of galaxies seen as the main driver of galaxy evolution
near-IR IFU work: $z \sim 2$ galaxies with high SFRs are in large part well ordered discs, and not major mergers.
High molecular gas fractions in normal massive star-forming galaxies in the young Universe

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The global picture: accretion-driven galaxy evolution

mm work: z~2 galaxies with high SFRs have significantly more gas than counterparts in the local Universe!
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)

\[ \text{SFR} \sim M_\ast^a (1+z)^b, \text{ where } a \sim 0.8, b \sim 2.5 \]

- Galaxies on the main sequence (MS) contribute \( \sim 90\% \) of the star formation.
- Duty cycles on the MS are high at 40-70\% (e.g. Noeske et al. 2007)
Star formation is regulated by the mass of gas in a reservoir, which itself is affected by the inflow rate, the star formation efficiency, and the mass loading factor of outflows.

Lilly et al. (2013), see also, e.g. Genel et al. (2008), Bouché et al. (2010), Davé et al. (2011,2012), Krumholz & Dekel (2012)
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\[ \Phi = (1 - R + \lambda) \cdot \text{SFR} + \frac{d m_{\text{gas}}}{dt} \]

Lilly et al. (2013), see also, e.g. Genel et al. (2008), Bouché et al. (2010), Davé et al. (2011,2012), Krumholz & Dekel (2012)
(1) Star formation efficiency, the gas reservoir and its redshift evolution
IRAM surveys for molecular gas in normal galaxies

direct molecular gas measurements for large, representative samples of normal star forming galaxies from both IRAM facilities

**COLD GASS**
Pls G. Kauffmann (MPA), C. Kramer (IRAM) 600h IRAM 30-m Large Programme +1000h Arecibo Programme for HI

365 SDSS-selected galaxies with 0.025<z<0.050, M*>10^{10}

**PHIBSS**
Pls L. Tacconi, R. Genzel (MPE), F. Combes (Paris) 500h IRAM PdBI Large Programmes

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

**Lensed galaxies**
PI 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
Cold gas in the SFR-M* plane

\[
\text{sSFR} = \frac{\text{SFR}}{M_*} = \frac{M_{\text{HI}}}{M_*} \frac{M_{\text{H}_2}}{M_{\text{HI}}} \frac{\text{SFR}}{M_{\text{H}_2}} = f_{\text{HI}} \ R_{\text{mol}} \ \text{SFE}
\]
Cold gas in the SFR-M* plane

\[ \text{sSFR} = f_{\text{HI}} \, R_{\text{mol}} \, \text{SFE} \]

"feeding" \rightarrow "consuming" \rightarrow "fueling"
Cold gas in the SFR-M* plane

\[ \text{sSFR} = f_{\text{HI}} R_{\text{mol}} \text{ SFE} \]

HI contents varies mostly across the MS, but also along (high SFR + low M* = more HI)
Cold gas in the SFR-M* plane

\[ \text{sSFR} = f_{\text{HI}} \cdot R_{\text{mol}} \cdot \text{SFE} \]

H2 contents varies almost exclusively across the MS (high SFR = more H2)
Star formation efficiency variations in the SFR-M* plane

BOTH H$_2$ contents and star formation efficiency vary across the MS
Gas and star formation efficiency explain the SFR-M* plane

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
Gas on the main sequence and star formation quenching

As galaxies evolve along the main sequence, they steadily consume their gas supplies.
Gas on the main sequence and star formation quenching

As galaxies evolve along the main sequence, they steadily consume their gas supplies and grow more prominent bulges.
Gas in the SFR-M* plan and what it teaches us

- **High star formation efficiency**
- **Danger zone** $M_{\text{HI}} \sim M_{\text{H}_2}$
- **Star-forming galaxies** $M_{\text{HI}} \sim 3M_{\text{H}_2}$
- **Passive galaxies** $M_{\text{HI}}/M^* \sim 2\%$
- **Early death** low $M^*$ but large bulge
Gas fractions increase up to $z=2$

The redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale.

Saintonge et al. (2013), Tacconi et al. (2013)
(2) Outflows and the return of gas and metals to the CGM/IGM
Direct observations of massive molecular outflows

outflows of molecular gas observed in OH and CO in systems hosting powerful starbursts or AGN

Sturm et al. (2011)

Feruglio et al. (2010)
Direct observations of massive molecular outflows

Although starbursts are effective in driving massive molecular outflows, the presence of an AGN may strongly enhance such outflows.

Cicone et al. (2013)
Direct observations of massive molecular outflows

Although starbursts are effective in driving massive molecular outflows, the presence of an AGN may strongly enhance such outflows.

but how about normal star-forming galaxies?

Cicone et al. (2013)
(3) Inflows and the feeding of the galaxy system
Different modes of gas accretion

Keres et al. (2005)

Different modes of gas accretion

In simulations, almost all of the star formation is due to gas accreted in the “cold mode”

Even at $z=0$ there is a need for the gas reservoirs to be replenished ($t_{\text{dep}} \ll t_{\text{Hubble}}$)

van de Voort et al. (2011)
Observational evidence for cold flows?

Observations of the circumgalactic medium (CGM) with HST/COS

Other suggestions that Lyman-limit systems are actually cold flows…

Unlikely that the gas detected is predominantly new material, either from ‘cold’ or ‘hot’ flows.

Observations of inward-moving gas, but may not match the specifications of cold flows. Can also use kinematic clues (e.g. Bouché et al. 2013)

Tumlinson et al. (2011)

Fumagalli et al. (2011)
Conclusion and outlook

Significant evidence for star formation and stellar mass growth of galaxies to be driven by the properties of the gas reservoir.
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What is the role of environment in regulating the gas supply of galaxies at different epochs?
Conclusion and outlook

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What is the role of environment in regulating the gas supply of galaxies at different epochs?

upcoming facilities will help getting the answers!