ALMA CH$^+$(1-0) detections of starburst galaxies at z $\sim$2.5

Massive turbulent reservoirs unveiled

Edith Falgarone  ENS & Observatoire de Paris

Zwaan M., Ivison R.J., Andreani P., Oteo I. ESO Garching
Godard B.  ENS & Observatoire de Paris
Bergin E.A. University of Michigan
Walter F. MPIA, Heidelberg
Omont A. Institut d’Astrophysique de Paris
Bournaud F., Elbaz D. CEA/AIM, Saclay
Bussmann S. Cornell University

« The Hydride Toolbox »,
Cosmic star formation

Peak of cosmic star formation history at z~2: most stars and galaxies seen today formed at that epoch.

Grand challenges of cosmological simulations:

- Star/galaxy formation runs too fast: observed timescales for cosmic star formation ~ 1 to 2 Gyr
  
  Schreiber + 2015

- >> timescales imposed by the growth of DM structures
  
  Somerville & Davé + 2015

- Somewhat alleviated by stellar- and AGN-driven feedback
  
  Schaye + 2015

- the cold ($10^4$ K) streams predicted to feed galaxy growth have never been observed Narayanan + 2015

Schaye + 2015

Madau & Dickinson 2014
ALMA CH$^+$ project: search for large turbulent interfaces

- 6 targets
  - H-ATLAs and HerMES surveys
  - Bussmann + 2013
- Redshift: $z = 2 - 2.6$
- Lens magnification: $\mu = 4 - 35$
- Oteo + in prep.

**Starburst galaxies**

FIR luminosity: $L_{\text{FIR}}$ up to $10^{13} L_{\text{sun}}$

$\Rightarrow SFR \sim 280 - 1330 M_{\text{sun}}$/yr
- Kennicutt 1998

**Formation of large turbulent interfaces**

at the interface cold streams-growing galaxy

- = buffers of mass and energy

Ceverino + 2010,
Gabor & Bournaud, 2013, 2014

$\Rightarrow SFR \sim 10^3 \times$ galactic average in $10^6 \times$ smaller volume
Why CH⁺?

- High critical density $= 10^7$ cm$^{-3}$
  - in absorption: $n_H < 100$ cm$^{-3}$
- Highly endothermic formation: $\text{C}^+ + \text{H}_2 \xrightarrow{E_{\text{form}} = 0.4 \text{ eV}} \text{CH}_3^+$
  - need supra-thermal energy
- Fast destruction by reactive collisions with H and H$_2$ → CH$_3^+$
  - lifetime $t \sim 1$ year in diffuse gas

$$\dot{E} = \mathcal{N}(\text{CH}^+) \frac{E_{\text{form}}}{t}$$

= rate of the energy supply needed to sustain $\mathcal{N}(\text{CH}^+)$ molecules in the beam

$\dot{E} \sim 10^{-2}$ to $10^{-3}$ turbulent energy transfer rate

Godard + 2014

CH⁺ absorption is a marker of the dissipation sites of supra-thermal energy in diffuse gas
ALMA 350µm rest-frame maps

Lens models $\rightarrow r_{\text{SMG}} = 0.5 - 1.2$ kpc

In Planck cosmology 0.4 arcsec $\rightarrow$ 3.3 kpc at $z=2.3$

Oteo + in prep.
**ALMA CH\(^+\)(1-0) spectra**

Absorption: detected in 5 sources out of 6 → lifetime \(\sim t_{SB}\)  
linewidths 230 – 580 km/s, optical depths 0.25 – 1.2 in 100 km/s bins  

Broad emission: FWZI up to 2500 km/s
CH$^+$ emission lines much broader than known CO lines → not from PDRs sharing the dynamics of SB cores
<table>
<thead>
<tr>
<th>Name</th>
<th>CH$^+$ emission</th>
<th>CH$^+$ absorption</th>
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<tbody>
<tr>
<td>SDP17</td>
<td>✓</td>
<td>blue</td>
</tr>
<tr>
<td>SDP130</td>
<td>✓</td>
<td>-</td>
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<tr>
<td>NAv1.144</td>
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<td>blue centre?</td>
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<td>centre</td>
</tr>
<tr>
<td>Eyelash</td>
<td>✓</td>
<td>red</td>
</tr>
</tbody>
</table>

Outflows? Inflows?
→ Turbulence in low density gas likely driven by outflows
What are the line profiles telling us?

- Concomitance broad emission / deep absorption $\rightarrow$ processes tied together
- Similar emission linewidths for SFR $\times$ 5 $\rightarrow$ hot gas pressure driven outflows

\[ v_{\text{out}} \sim \sqrt{3} \times 500 \, \text{km s}^{-1} \left(\frac{T}{4 \times 10^7 \, \text{K}}\right)^{1/2} \]

- Different absorption linewidths $\rightarrow$ gravitationally bound

\[ \Delta v_{\text{abs}} \sim v_{\text{esc}}(r) = \left(\frac{2GM_{\text{tot}}}{r}\right)^{1/2} \]

at $r = \Delta v_{\text{abs}} t_{\text{SB}}$
The diffuse turbulent reservoirs

\( N(\text{CH}^+) = 5 - 8 \times 10^{14} \text{ cm}^{-2} \)

\( r_{\text{TR}} = 8 - 20 \text{ kpc} \)

\( [\text{CH}^+] / [\text{H}] = 0.4 - 2.5 \times 10^{-8} \)

\( M_{\text{TR}} = 5 - 6 \times 10^{10} \text{ M}_\odot \)

Kinetic luminosity:

\[ L_{\text{TR}} \propto \frac{M_{\text{TR}} \Delta v_{\text{abs}}^2}{t_{\text{SB}}} = 0.6 - 2.2 \times 10^9 \text{ L}_\odot \propto \text{SFR} \]

\( \rightarrow \) mass outflow rate \( \sim \) SFR
High velocity gas seen in emission

No shocks $v_{\text{sh}} > 90$ km/s: radiative precursors

→ Myriads of low velocity $v_{\text{sh}} < 40$ km/s irradiated shocks

Pre-shock density $10^4$ cm$^{-3}$, $v_{\text{sh}} = 20$ km/s

$\Rightarrow$ N(CH$^+$) = $10^{14}$ cm$^{-2}$

Shock density $> 10^5$ cm$^{-3}$, optically thin CH$^+$(1-0) lines

Result depends weakly on density

Origin?

Stellar- or AGN-driven outflows within the SB cores, tidal shocks in mergers, cold stream collision with the galaxies?

Lesaffre et al. 2013,
Falgarone et al. 2010
Godard + in prep
Kpc-scale shock in the Stephan’s quintet

Energy of a large-scale collision

\[ v_{\text{rel}} = 500 \text{ – } 700 \text{ km/s} \rightarrow \text{shock heated gas} \]

25% radiated in X-rays
75% radiated in H\(_2\) pure rotational lines

Shock distribution

Cluver + 2010

Lesaffre + 2013

Appleton + 2013
Guillard + 2012 and in prep.
In summary

Regardless of the energy drivers (feedback from stellar- or AGN-driven outflows, infalling cold streams, major mergers, ...)

- massive turbulent interfaces
  = buffers of mass and gravitational energy
- turbulence likely driven by outflows
- multi-phase turbulence (shocks, diffuse halo)

CH⁺ being a very specific tracer of
(i) dissipation of turbulent energy in diffuse gas
(ii) highly irradiated dense gas in shocks
opens an entirely new field of investigation of galaxy formation in the high-z universe