The role of molecules in star formation

Paul Clark, Simon Glover, Ralf Klessen
(ITA, ZAH der Universität Heidelberg)

Ian Bonnell
(St Andrews University)
Correlation between molecular gas and the SFR

Bigiel et al. (2008)

Has lead to assumption that molecular gas is needed for star formation:

- Schaye 2004
- Krumholz & McKee 2005
- Elmegreen 2007
- Krumholz et al. 2009
Can now test the effect of chemistry on gas thermodynamics

- Use time dependent chemical network to track H$_2$ + CO formation (see Glover & Clark 2012b).
- Implemented in Gadget2 (Springel 2005).
- Sink particle to model the star formation (Bate, Bonnell & Price 1995).
- ISRF attenuation treated by TreeCol (Clark, Glover & Klessen 2012a).
- Self-consistent gas and dust temperatures.

Simplified PDR code that runs alongside a fluid code

Glover et al. (2010)
Glover & Clark (2012a)

- $10^4 \, M_\odot$ clouds, with $n \sim 300 \, \text{cm}^{-3}$.
- Initially virialised turbulent velocity field, $v_{\text{RMS}} \sim 2.5 \, \text{km/s}$ ($P(k) \propto k^{-4}$).
- ‘Black + Drain’ ISRF ($1.7G_0$) + $3 \times 10^{-17} \, \text{s}^{-1}$ CR-ionisation rate.
- Gas has ‘solar’ composition (C, Si, O, dust, etc).

Increase the complexity of the chemical model

- Atomic gas
- $\text{H}_2$ formation
- $\text{H}_2 + \text{CO}$ formation
- No shielding

Shielding on

Atomic ICs + Molecular ICs
Do the star formation rates differ?

Glover & Clark (2012a)

Clouds with shielding
- SFRs are the same!
- Atomic gas is slightly delayed:
  - Higher mean molecular weight
  - Slightly higher Jeans mass.

Clouds without shielding
- Eventually forms a massive star at about 9 Myr.
- Looks almost like Pop III star formation.
Glover & Clark (2012a)

- Temperature distribution largely insensitive to the gas chemistry.
- Formation of H\textsubscript{2} heats gas.
- CO allows gas to cool down to CMB.
- Dust-gas coupling at n > 10\textsuperscript{5} cm\textsuperscript{-3} regulates temperature.
- Dust temperature set by ISRF + CR-ionisation.
Heating/cooling processes (no CO)

Glover & Clark (2012a)
Heating/cooling processes (with CO)
Summary so far:

- Molecule formation has very little effect on the rate at which stars form.
- Molecular gas and star formation are correlated because they both require well-shielded gas.

Glover & Clark (2012a)
So why do we care?

Low metallicity star formation:

- Observed SFE to CO luminosity ratio \( (\text{SFE}/W_{\text{CO}}) \) is systematically higher as we look at progressively more metal-poor galaxies.
  - Taylor, Kobulnicky & Skillman (1998); Leroy et al. (2007); Schruba et al. (2011).

- So either:
  - metal-poor gas forms stars more efficiently than metal-rich gas (unlikely).
  - \( X_{\text{CO}} (N_{\text{H2}}/W_{\text{CO}}) \) is much higher than Milky Way value.
SFR + CO formation with decreasing metallicity

$Z \odot, 0.3 \odot, 0.1 \odot, 0.03 \odot, 0.01 \odot$

Glover & Clark (2012c)
$H_2$ formation with $Z$
Observed SFR/W_{\text{CO}} strongly depends on Z!

Glover & Clark (2012c)


X-factor with metallicity

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<th>Run</th>
<th>$W_{\text{CO, max}}$</th>
<th>$W_{\text{CO, mean}}$</th>
<th>$X_{\text{CO}} / X_{\text{CO, gal}}$</th>
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</table>

Glover & Clark (2012b)
Temperature - density distribution

Glover & Clark (2012c)
Summary so far:

- At low metallicities, where molecular formation becomes difficult, star formation proceeds in largely atomic gas.
- Star formation rate is insensitive to the metallicity of the gas.
- ‘X-factor’ is strongly metallicity-dependent (and likely time-dependent).

Glover & Clark (2012b)
But those clouds were pre-assembled...

... what happens when we try to form them?

Cloud formation in colliding flows:

Clark et al. (2012b)
Delay between CO formation and star formation?

- CO appears 2 Myr before star formation in both flows.
- H$_2$ can appear much earlier (depending on flow).

Clark et al. (2012b)
Observational time-sequence

$^{12}$CO (1-0)

slow flow
\[ \text{time} = t_{\text{sf}} - 2\,\text{Myr} \]

fast flow
\[ \text{time} = t_{\text{sf}} - 2\,\text{Myr} \]
Observational time-sequence

$^{12}\text{CO}$

(1-0)

Clark et al. (2012b)

slow flow
time = $t_{SR} - 1\text{Myr}$

fast flow
time = $t_{SR} - 1\text{Myr}$

2.6 pc
Observational time-sequence

$^{12}\text{CO}$

\((1 - 0)\)

slow flow

time = $t_{\text{SR}}$

2.6 pc

fast flow

time = $t_{\text{SR}}$
Observational time-sequence

$^{12}\text{CO}$

(1 - 0)

slow flow

time $= t_{\text{sf}} + 0.8 \text{ Myr}$

fast flow

time $= t_{\text{sf}} + 0.8 \text{ Myr}$

2.6 pc
Summary:

• CO is tracer of star-forming gas, but is **not** needed for stars to form.
• At lower metallicities, CO is confined to denser, hotter cores.
• $X_{CO}$ varies dramatically as we go to lower metallicities.
• CO seems to precede star formation by about 2 Myr under local galactic conditions.