Molecular Hydrogen for RAMSES

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Carina Nebula, Credit: NASA, ESA, N. Smith, and The Hubble Heritage Team
Outline

1. An introduction to $\text{H}_2$
2. Ramses-RT with $\text{H}_2$
3. Full galaxy simulation
**H₂ in Galaxies**

- Most common molecule in the Universe
- Important to cooling the interstellar medium
- No dipole moment and is light, leading to high emission temperature
- Difficult to detect directly, usually inferred from CO by conversion factor
- Dense, cold molecular clouds are linked to star formation
Molecular Cloud Schematics

Lyman Werner radiation (11.20-13.60 eV)

Ionizing radiation (≥ 13.60 eV for HI, ≥ 15.42 eV for H$_2$)

easily observable?

- **HII gas**
- **HI gas**
- **H$_2$ gas**
- **CO gas**
- **HCN gas**
H₂ Self-Shielding

- Not every absorption of a Lyman-Werner photon (11.2 to 13.6 eV) leads to dissociation
- Different lines of Lyman-Werner photons dissociate H₂ at different rates
- Stronger lines absorbed at cloud surface, weaker lines sneak deeper
- Heisenberg uncertainty means that finite molecular excitation time leads to natural line width
- The strong lines interfere with the weak lines
- Deeper into H₂ cloud, absorption becomes harder

Source: Haiman et al. 2000
Ramses-RT

- Rosdahl et al. 2013
- Moment-based radiative transfer scheme for RAMSES
- Computation independent of source number
- Non-equilibrium chemistry of HI, HII, HeI, HeII, and HeIII coupled to ionising photon groups and thermal state of gas
Adding $\text{H}_2$ to RAMSES-RT

\[
\dot{n}_{\text{H}_2} = \alpha_{\text{H}_2}^{Z}(T) Z_f d n_{\text{H}_1} n_{\text{H}_2} + \alpha_{\text{H}_2}^{\text{GP}}(T) n_{\text{H}_1} n_{e} \\
+ \beta_{3B}(T) n_{\text{H}_1}^2 (n_{\text{H}_1} + n_{\text{H}_2} / 8) \\
- \beta_{\text{H}_2\text{H}_1}(T) n_{\text{H}_1} n_{\text{H}_2} - \beta_{\text{H}_2\text{H}_2}(T) n_{\text{H}_2}^2 \\
- \Gamma_{\text{H}_2}^{\text{LW}}(N_{\text{H}_2}) n_{\text{H}_2} - \Gamma_{\text{H}_2}^{+}(N_{\text{H}_1}) n_{\text{H}_2} - \xi_{\text{H}_2} n_{\text{H}_2}
\]

Formation on dust (Hollenbach & McKee 1979; Jura 1974; Gry et al. 2002; Habart et al. 2004)
Gas-phase formation (McKee & Krumholz 2012)
Formation by three-body collisions (Forrey 2013; Palla et al. 1983)
Collisional destruction with HI (Dove & Mandy 1986)
Collisional destruction with itself (Martin et al. 1998)
Photodissociation by Lyman-Werner photons (Sternberg et al. 2014)
Photoionisation by ionising photons (Abel et al. 1997)
Cosmic ray ionisation (Indriolo & McCall 2012; Gong et al. 2017; Glassgold & Langer 1974)
Additional Thermal Processes

- Photoelectric effect heating (Bakes & Tielens 1994, Wolfire et al. 2003)
- Heat from UV pumping (Baczynski 2015, Draine & Bertoldi 1996, Burton et al. 1990)
- H$_2$ formation heating (Hollenbach & McKee, Omukair 2000)
- Cosmic ray ionization heating (Glassgold et al. 2012)
- H$_2$ collisional destruction cooling (Halle & Combes 2013, Hollenbach & McKee 1979)
Previous Self-Shielding Models

- Galaxy simulations use the Draine and Bertoldi 1996 self-shielding as a function of column density
- Decreases H\(_2\) destruction
- Problems: simulations use volume density and ray tracing is expensive for galaxies with multiple sources
- Many approximations to convert column density to volume density, local and non-local

\[
f_{\text{shield}}(N_2) = \frac{0.965}{(1 + x/b_5)^2} + \frac{0.035}{(1 + x)^{0.5}} \times \exp \left[ -8.5 \times 10^{-4}(1 + x)^{0.5} \right]
\]

\(x = N_2/10^{14}\)

b is a constant

Our Self-Shielding Model

• Takes advantage of moment-based radiative transfer that treats photons like a fluid

• Instead of decreasing H\textsubscript{2} destruction, we enhance Lyman-Werner destruction

• Use a constant factor, S; calibrated with Bialy et al. 2016 HI-H\textsubscript{2} transition depth

• Cumulative destruction of LW photons while they travel through each cell is similar

\[ D_{LW} = c\sigma_{LW}n_{H2} \rightarrow Sc\sigma_{LW}n_{H2} \]
Originally describes radiation from an OB star ionising an atomic medium.

We describe ionizing and dissociating radiation in an atomic and molecular medium.

Molecular and atomic fronts grow according to analytical expressions.

Milky Way-like, isolated disc galaxy (from the AGORA project, Kim et al. 2016)
Resolution 6 pc, 400 kpc box
Star formation recipe independent of $\text{H}_2$, is total gas density-based (Rasera & Teyssier 2006)
Delayed cooling thermal feedback for supernovae (Teyssier et al. 2013)
Galaxy!

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Star formation recipe independent of H$_2$, is total gas density-based (Rasera & Teyssier 2006)
Delayed cooling thermal feedback for supernovae (Teyssier et al. 2013)
• Established, observed relation between neutral gas and SFR (Schmidt (1959) and Kennicutt (1998))
• More recently discovered relation between $\text{H}_2$ and SFR (e.g. Bigiel et al. 2008)
• We match both, aside from quenched central points
• Scruba 2011 extend this relation to lower densities, and we match fall in HI-$\text{H}_2$ relation
Phase Diagrams

All plots weighted by gas mass fraction

- Unresolved HII regions
- Star formation threshold

HII sparse, hot gas
H$_2$ cold, dense gas
HI in between
Cannot resolve 100% molecular regions or HII regions around young stars

Where is the H$_2$?

- 50% of H$_2$ is at densities 37.8 cm$^{-3}$ and lower
- 50% of H$_2$ is at fractions 0.57 and lower
Clump Finding With PHEW

Gas Density

H$_2$

Radiation

$\nu$ [cm$^{-3}$]

$2\cdot$H$_2$ fraction

$\Gamma_{\nu}$ [s$^{-1}$]

10 Kpc
Conclusions

- Successfully modelled non-equilibrium H$_2$ chemistry using local methods with Ramses-RT
- Introduced new radiative transfer-based self-shielding model for galaxy simulations
- Tested model in idealised situations against benchmark models to demonstrate robustness
- Realistic galaxy
- Much of the H$_2$ gas is diffuse and mixed with HI
- In progress: CO chemistry to investigate the CO-H$_2$ conversion factor and the existence of a “CO-dark” H$_2$ component of the ISM

Photodissociation regions (PDRs) UV dominated (6 to 13.2 eV) and host most galactic atomic and molecular gas.

Roellig 2013 benchmark comparison of 10 PDR codes.

PDR codes are 1D so can treat self-shielding exactly.

We reproduce transition point, but not shape.

Radial Profile

Reproduce central H\textsubscript{2} spike and flat HI profile
SFR trends mimic H\textsubscript{2} trends, except for galactic centre
Central bulge may cause morphological quenching
Surface density and SFR numbers are similar to observed galaxies around Milky Way mass
- Clouds are 96% molecular
- Slightly more at medium masses than Milky Way, fewer low mass clouds
- Inner and outer galaxy cloud populations show no difference