Heating and Cooling Processes

Inga Kamp, KROME summer school November 26 – November 28, 2018, Concepcion, Chile
Heating and Cooling Processes

1. Introduction
2. Dust heating/cooling
3. Line heating/cooling
   I. LTE
   II. non-LTE
4. Other Processes
   I. Photoelectric and PAH heating
   II. CR and X-ray heating
   III. Ionisation heating
   IV. $\text{H}_2$: a special case
   V. Dust thermal accommodation
   VI. Bremsstrahlung
   VII. Viscous heating
   VIII. Chemical heating
5. Exercise
6. Examples
   I. Planet forming disk

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Literature


Hollenbach & Tielens (1997), *Dense Photodissociation Regions*, ARAA 35, 179

1. Introduction

From observations to interpretation

A quantitative interpretation of line emission often requires dynamical/radiation/thermal/chemical models of the studied astrophysical environment.
1. Introduction

Heating and cooling of a gas

\[
\frac{de}{dt} = -P \frac{dV}{dt} + \sum_i \rho \Gamma_i - \sum_k \rho \Lambda_k
\]

change in internal energy

If the cooling timescale (\(\tau_{cool}\)) is much faster than the dynamical timescale (\(\tau_{dyn}\)):

\[
\sum_i \rho \Gamma_i = \sum_k \rho \Lambda_k \quad \Rightarrow T_{gas}
\]

If collisional coupling between gas and dust is inefficient: \(T_{gas} \neq T_{dust}\)
1. Introduction

How it all ties together

Physical structure of the object (+ element abundances, dust properties)

Dust opacity, dust temperature

Radiation field (e.g. photons/s/cm²/Hz)

Gas (+dust surface) chemistry

Gas energy balance (gas temperature)

Ray tracing (observables e.g. spectrum, line profile)

possibly update physical model (e.g. hydrostatic equilibrium, pressure equilibrium, thermal stability of dust/clouds)
1. Introduction

How it all ties together

- Physical structure of the object (+ element abundances, dust properties)
- Dust opacity, dust temperature
- Gas (+dust surface) chemistry
- Gas energy balance (gas temperature)
- Radiation field (e.g. photons/s/cm²/Hz)
- Interaction of dust with radiation
- Interaction of gas with radiation
- Ray tracing (observables e.g. spectrum, line profile)

possibly update physical model (e.g. hydrostatic equilibrium, pressure equilibrium, thermal stability of dust/clouds)
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Dust opacities

Input data for models:

• grain size distribution
• grain composition (e.g. volume fraction silicate, amorphous carbon, vacuum, ice, …)

\[
\kappa_{\nu}^{\text{abs}} = \frac{Q_{\text{abs}}(\nu)\pi a^2}{4\frac{\pi a^3}{3}\rho_{\text{grain}}}
\]

for single grain size \(a\)

=> can be generalized to grain size distribution using moments of the distribution \(<a^2>, <a^3>\)
2. Dust heating and cooling

**Dust radiative equilibrium**

Energy can be added or removed from the grain by absorption or emission of photons, or by inelastic collisions with atoms or molecules from the gas (grain heating).

\[
\int \frac{u_\nu}{h\nu} \cdot c \cdot h\nu \cdot Q_{abs}(\nu)\pi a^2 d\nu = \int 4\pi a^2 B_\nu(T_{dust})Q_{abs}(\nu)\pi a^2 d\nu
\]

Solving for \(T_{dust}\) requires continuum radiative transfer.

often neglected, because small – but not in accretion disks

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2. Dust heating and cooling

Dust temperature

A day in the life of four carbonaceous grains, heated by the local interstellar radiation field. \( \tau_{abs} \) is the mean time between photon absorptions.

\[ \tau_{abs} \] is the mean time between photon absorptions.

1 hour = 3600 s

Definition of temperature for very small grains:

instantaneous vibrational temperature = temperature \( T(E) \) at which the expectation value of the energy would be equal to the actual grain energy

[Draine 2003]
Continuum radiative transfer

Radiative transfer equation

\[
\frac{dI_\nu}{ds} = -\alpha_{\nu}^{dust} \left( S_\nu - I_\nu \right) \quad \text{with} \quad S_\nu = \frac{j_{\nu}^{dust}}{\alpha_{\nu}^{dust}}
\]

\[
j_{\nu}^{dust} = \alpha_{\nu}^{dust,abs} B(T_{dust}) + \alpha_{\nu}^{dust,sca} J_{\nu}
\]

\[
\alpha_{\nu}^{dust} = \alpha_{\nu}^{dust,abs} + \alpha_{\nu}^{dust,sca}
\]

\[
\begin{array}{l}
I_\nu \quad – \text{intensity [erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}] \\
\nu \quad – \text{frequency} \\
s \quad – \text{physical path length} \\
S_\nu \quad – \text{source function} \\
a_{\nu}^{dust} \quad – \text{dust extinction coefficient [cm}^{-1}] \\
a_{\nu}^{dust,abs} \quad – \text{dust absorption coefficient} \\
a_{\nu}^{dust,sca} \quad – \text{dust scattering coefficient} \\
j_{\nu}^{dust} \quad – \text{continuum emission coefficient}
\end{array}
\]
2. Dust heating and cooling

Gas Temperature

de the gas has many possibilities to heat and cool due to the presence of a large variety of atoms/molecules (forest of line transitions, ionization, dissociation processes etc.)

$$\sum_i \Gamma_i = \sum_j \Lambda_j$$

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<td>O I, C II, C I fine-structure lines</td>
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<td>PAH heating</td>
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<td>viscous ((\alpha)) heating</td>
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<td>cosmic rays</td>
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<td>C photo-ionisation</td>
<td>o/p H(_2) quadrupole lines</td>
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<td>Si II, S II, Fe II semi-forbidden lines</td>
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<td>H(_2) formation on grains</td>
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<td>H(_2) photodissociation</td>
<td>Mg II h&amp;k lines</td>
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<td>IR background line heating</td>
<td>O I 6300 Å line</td>
</tr>
<tr>
<td>X-ray heating</td>
<td>thermal accommodation on grains</td>
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</table>

and many other molecules

and many other atomic lines
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6. Examples
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Local Thermodynamic Equilibrium

if collisions dominate, level populations for an atom/molecule follow from the Boltzmann equation

\[
\frac{n_i}{n_j} = \frac{g_i}{g_j} e^{-\Delta E/kT}
\]

rotational level populations are often in LTE since their energies \( E_{\text{rot}} \) are often \( \ll 1 \text{ eV} \Rightarrow \) collisions can easily thermalize them

The critical density of a line \( n_{\text{crit}} = \frac{A_{ul}}{\gamma_{ul}} \)

is a measure for the density at which LTE roughly holds
3. Line heating and cooling

**Local Thermodynamic Equilibrium**

The line emission (cooling) can be derived from the level populations

\[
\Lambda_k(\nu_{ij}) = n_i^{LTE} A_{ij} h\nu_{ij} \beta_{esc}(\tau_{ij})
\]

- \(\nu_{ij}\) – frequency of the line
- \(\tau_{ij}\) – optical depth of the line
- \(A_{ij}\) – spontaneous emission probability
- \(\beta_{esc}\) – escape probability
- \(n_i\) – population number of the upper level

With the escape probability

\[
\beta(\tau) = \frac{1}{2} \int_{-\infty}^{\infty} dx \phi(x) \int_{0}^{1} \exp(-\tau \phi(x)/\mu) d\mu
\]

[Avrett & Hummer 1965]

\[
\begin{cases}
1 - \exp(-2.34\tau) & , \tau < 7 \\
\frac{4\tau}{4.68\tau} & , \tau \geq 7 \\
\end{cases}
\]

Different in cases of large velocity gradients
Velocity gradients

Why would velocity gradients impact line RT?

radially expanding velocity field

\[ v = \left( \frac{dv}{dr} \right) r \]
3. Line heating and cooling

Velocity gradients

Why would velocity gradients impact line RT?

Large Velocity Gradient (LVG) approximation

\[ \Delta \nu_{ij} = \nu_{ij} \frac{(v(r_n) - v(r_{n-1}))}{c} \]

if \( \Delta \nu \) from one cell to the next is larger than the line width, the photon is “shifted out of the line” and can escape

\[ \beta_{esc} = \frac{1 - e^{-\tau_{LVG}}}{\tau_{LVG}} \]  
[Sobolev 1957]

\( \tau_{LVG} \) is the total optical depth along the path for any frequency

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3. Line heating and cooling

Velocity gradients

Disks have a Keplerian velocity field.
LVG approximation does not work since a line can interact with itself at various locations along a ray (e.g. top and bottom of the disk, near- and far-side).

[Beckwith & Sargent 1993, Pontoppidan et al. 2009]
3. Line heating and cooling

Statistical Equilibrium

if LTE does not hold, we need to solve the detailed equations of statistical equilibrium (SE) for each energy level \(i\)

\[
\frac{dn_i}{dt} = \sum_{j>i} n_j (A_{ji} + B_{ji} P(\nu_{ji})) + \sum_{j<i} n_j B_{ji} P(\nu_{ji}) + \sum_{j \neq i} n_j C_{ji}
\]

addition from higher levels
due to spontaneous + stimulated emission
addition from lower levels
due to absorption
collisions ending in level \(i\)

\[
-n_i \sum_{j<i} (A_{ij} + B_{ij} P(\nu_{ij})) - n_i \sum_{j>i} B_{ij} P(\nu_{ij}) - n_i \sum_{j \neq i} C_{ij}
\]

loss into lower levels
due to spontaneous + stimulated emission
loss into higher levels
due to absorption
collisions leaving level \(i\)

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>(n_i)</td>
<td>population of level (i)</td>
</tr>
<tr>
<td>(\nu_{ij})</td>
<td>frequency of the line</td>
</tr>
<tr>
<td>(P(\nu_{ij}))</td>
<td>radiation field at frequency (\nu_{ij})</td>
</tr>
<tr>
<td>(A_{ij})</td>
<td>Einstein A coefficient (spontaneous emission)</td>
</tr>
<tr>
<td>(B_{ji})</td>
<td>Einstein B coefficient (absorption)</td>
</tr>
<tr>
<td>(B_{ij})</td>
<td>Einstein B coefficient (stimulated emission)</td>
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3. Line heating and cooling

**Statistical Equilibrium**

if LTE does not hold, we need to solve the detailed equations of statistical equilibrium (SE) for each energy level $i$

\[
\frac{dn_i}{dt} = \sum_{j \geq i} n_j (A_{ji} + B_{ji} P(\nu_{ij})) + \sum_{j < i} n_j B_{ij} P(\nu_{ij}) + n_i \sum_{j \neq i} n_j C_{ji} \\
- n_i \sum_{j < i} (A_{ij} + B_{ij} P(\nu_{ij})) - n_i \sum_{j > i} B_{ij} P(\nu_{ij}) - n_i \sum_{j \neq i} n_j C_{ij}
\]

with the stimulated emission coefficient

\[
B_{ji} = \frac{c^2}{2h\nu^3} A_{ji}
\]

and the relation between stimulated emission and absorption coefficient

\[
g_i B_{ij} = g_j B_{ji}
\]
3. Line heating and cooling

Statistical Equilibrium

\[
\frac{dn_i}{dt} = \sum_{j>i} n_j (A_{ji} + B_{ji} P(\nu_{ji})) + \sum_{j<i} n_j B_{ij} P(\nu_{ij}) + n_i \sum_{j\neq i} n_j C_{ji} \\
- n_i \sum_{j<i} (A_{ij} + B_{ij} P(\nu_{ij})) - n_i \sum_{j>i} B_{ij} P(\nu_{ij}) - n_i \sum_{j\neq i} n_j C_{ij}
\]

Solve numerically using e.g. Newton-Raphson

\[
= \text{level population numbers for rotational, vibrational levels of all electronic states}
\]

\[
= \text{for some purposes (cold low density environments), only ground electronic, vibrational state populated, hence only rotational level populations needed}
\]

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3. Line heating and cooling

The two-level atom

\[ \frac{n_1}{n_0} = \frac{A_{10} \frac{c^2}{2h \nu^3} g_1 P(\nu_{10}) + C_{01}}{A_{10} + A_{10} \frac{c^2}{2h \nu^3} P(\nu_{10}) + C_{10}} \]

without background radiation:

\[ \frac{n_1}{n_0} = \frac{C_{01}}{A_{10} + C_{10}} \]

What happens if collisions are negligible?

\[ \frac{n_1}{n_0} = \frac{g_1}{g_0} \frac{c^2}{2h \nu^3} P(\nu_{10}) \]

if \( P(\nu_{10}) \) is a blackbody radiation field with \( T_{gas} \)

\[ \frac{n_1}{n_0} = \frac{g_1}{g_0} \frac{c^2}{2h \nu^3} \left( \frac{2h \nu^3}{c^2} e^{\frac{h \nu_{10}}{k T_{gas}}} - 1 \right) = \frac{g_1}{g_0} e^{-\frac{h \nu_{10}}{k T_{gas}}} \]

radiation can also produce LTE!
3. Line heating and cooling

The two-level atom

\[
\frac{n_1}{n_0} = \frac{A_{10} c^2 g_1}{2 h \nu^3 g_0} P(\nu_{10}) + C_{01} \quad \text{[CII] 158 \, \mu m}
\]

without background radiation:

\[
\frac{n_1}{n_0} = \frac{C_{01}}{A_{10} + C_{10}}
\]

What happens if collisions are negligible?

\[
\frac{n_1}{n_0} = \frac{g_1 c^2}{g_0 (1 + \frac{c^2}{2 h \nu^3}) P(\nu_{10})}
\]

if \( P(\nu_{10}) \) is a blackbody radiation field with \( T_{gas} \)

\[
\frac{n_1}{n_0} = \frac{g_1 c^2}{g_0 \left( \frac{2 h \nu^3}{c^2} \right) \left( e^{\frac{h \nu_{10}}{k T_{gas}}} - 1 \right)} = \frac{g_1}{g_0} e^{-\frac{h \nu_{10}}{k T_{gas}}}
\]

radiation can also produce LTE!
3. Line heating and cooling

Statistical Equilibrium

CO molecule

UV pumping

IR pumping

LTE

often a good assumption

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3. Line heating and cooling

Heating and cooling of a gas

For the net cooling rate, one can either calculate the net creation rate of photon energy (radiative approach), or one can calculate the total destruction rate of thermal energy (collisional approach)

\[ \Gamma = \begin{cases} \Gamma_{\text{col}}, & \Gamma_{\text{rad}} > \Gamma_{\text{col}} \\ \Gamma_{\text{rad}}, & \Gamma_{\text{rad}} \leq \Gamma_{\text{col}} \end{cases} \]

\[ \Lambda = \begin{cases} \Lambda_{\text{col}}, & \Gamma_{\text{rad}} > \Gamma_{\text{col}} \\ \Lambda_{\text{rad}}, & \Gamma_{\text{rad}} \leq \Gamma_{\text{col}} \end{cases} \]

with

\[ \Gamma_{\text{rad}} = \sum_{u \succ l} n_u \Delta E_{ul} \left( P_{ul}^{\text{pump}} B_{ul} f_{\nu_{ul}}^{\text{cont}} \right) \]

\[ \Lambda_{\text{rad}} = \sum_{u \succ l} n_u \Delta E_{ul} \left( P_{ul}^{\text{esc}} A_{ul} + P_{ul}^{\text{pump}} B_{ul} f_{\nu_{ul}}^{\text{cont}} \right) \]

\[ \Gamma_{\text{col}} = \sum_{u \succ l} n_u C_{ul} \Delta E_{ul} \]

\[ \Lambda_{\text{col}} = \sum_{u \succ l} n_l C_{lu} \Delta E_{ul} \]
3. Line heating and cooling

Statistical Equilibrium

At different temperatures, different main coolants will dominate the energy balance: at low temperatures (few 100 K) the fine structure lines, at high temperatures (few 1000 K) atomic lines.
3. Line heating and cooling

**Statistical Equilibrium**

**H/H\textsubscript{2} C\textsuperscript{+}/C/CO**

**C\textsuperscript{+}/C/CO**

```latex
\text{H/H}_2 \, \text{C}^+ / \text{C/CO}
```

- dense PDR with $n = 2.3 \times 10^5$ cm$^{-3}$, $G_0 = 10^5$

[Hollenbach & Tielens 1997]

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4. Other processes

**Photoelectric heating**

Photons with $10 \leq h\nu \leq 13.6\, eV$ cannot ionize hydrogen, but can ionize dust grains $\Rightarrow$ ejection of a photoelectron.  

$$\Gamma_{PE} = \varepsilon_{\text{GRAIN}} n_{\text{dust}} \sigma_{\text{dust}} \chi$$

photoelectric heating rate

with the integrated FUV (912-2050 Å) radiation field

$$\chi = \frac{\int_{912}^{2050} \lambda u_{\lambda} d\lambda}{\int_{912}^{2050} \lambda u_{\lambda}^{\text{Draine}} d\lambda}$$

$\lambda u_{\lambda}$ photon energy density $[\text{erg/cm}^3]$ 

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<td>work function of bulk dust material</td>
</tr>
<tr>
<td>$Y$</td>
<td>electron yield</td>
</tr>
<tr>
<td>$\varepsilon_{\text{GRAIN}}$</td>
<td>efficiency of heating</td>
</tr>
<tr>
<td>$\Phi_C$</td>
<td>Coulomb potential of the dust grain</td>
</tr>
<tr>
<td>$\sigma_{\text{abs}}$</td>
<td>dust absorption cross section</td>
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4. Other processes

**Photoelectric heating**

Photons with $10 \leq h\nu \leq 13.6\text{eV}$ cannot ionize hydrogen, but can ionize dust grains $\Rightarrow$ ejection of a photoelectron. [Hollenbach & Tielens 1997]

$$\Gamma_{\text{PE}} = \varepsilon_{\text{GRAIN}} n_{\text{dust}} \sigma_{\text{dust}} \chi$$

photoelectric heating rate

with the integrated FUV (912-2050 Å) radiation field

$$\chi = \frac{\int\limits_{912}^{2050} \lambda \nu_{\lambda} d\lambda}{\int\limits_{912}^{2050} \lambda \nu_{\lambda}^{\text{Draine}} d\lambda}$$

Photon energy density [erg/cm$^3$]

---

$W$ – work function of bulk dust material

$Y$ – electron yield

$\varepsilon_{\text{GRAIN}}$ – efficiency of heating

$\Phi_C$ – Coulomb potential of the dust grain

$\sigma_{\text{abs}}$ – dust absorption cross section

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Other important heating processes

- **PAH heating**: depends on the size of the PAH, the radiation field and density

- **Cosmic Ray and X-ray heating**: high energy radiation produces super-thermal electrons through ionisation (e.g. K-shell) that heat the gas through Coulomb interactions with thermal electrons

- **Ionisation heating**: FUV radiation ionises metals and the electrons heat the gas (compared to CR and X-rays, FUV radiative transfer is more intertwined with dust and H$_2$ – shielding)

all depend on the radiation field (solving full RT) and CRs (attenuation into the medium)
4. Other processes

**PAH heating**

PAHs get charged according to the local radiation field, densities, PAH abundance

\[e_{PAH} \sim n \left( \frac{hv - IP}{hv} \right)\]

\[\Gamma_{PAH} = \frac{4\pi}{hc} \sum_k n_{PAH}^{k} \int_{\lambda_{thr}}^{912 \text{Å}} \sigma_{PAH}^{k}(v) \nu J_{\nu} Y_{\nu}^{k} s_{\nu}\left(hv - IP^{k}\right) d\lambda\]

PAH ionisation is heating

\[\Lambda_{PAH} = \sum_k n_{PAH}^{k} n_{e} k_{PAH}^{k}(T_{g}) \left(1.5 kT_{g}\right)\]

PAH recombination with free e\(-\) is cooling

\[\text{[Hollenbach & Tielens 1997]}\]

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- \(IP^{k}\) – Ionisation Potential of PAH\(^{k}\)
- \(n_{PAH}^{k}\) – PAH density
- \(n_e\) – electron density
- \(\sigma_{PAH}^{k}\) – PAH absorption cross section
- \(k_{PAH}^{k}\) – PAH recombination coefficient
- \(T_{gas}\) – gas temperature
- \(J_{\nu}\) – radiation field
- \(Y_{\nu}^{k}\) – photoelectron yield
- \(s_{\nu}\) – self-shielding factor
4. Other processes

Cosmic Ray and X-ray heating

High energy radiation produces super-thermal electrons through ionisation (e.g. K-shell) that heat the gas through Coulomb interactions with thermal electrons

\[
\Gamma_{X_{\text{ray}}} = \xi_{X_{\text{ray}}} \left( Q_{H}^{\text{Cou}} n_{H} + Q_{H_{2}}^{\text{Cou}} n_{H_{2}} + \ldots \right)
\]

[Dalgarno et al. 1999]

\[
\Gamma_{CR} = \xi_{CR} \left( Q_{H}^{CR} n_{H} + Q_{H_{2}}^{CR} n_{H_{2}} + \ldots \right)
\]

\[
\Gamma_{CR} \approx \xi_{CR} \left( 5.5 \cdot 10^{-12} n_{H} + 2.5 \cdot 10^{-11} n_{H_{2}} \right)
\]

for H/H2 mixture

\[\xi_{X_{\text{ray}}} \quad \text{– X-ray primary ionisation rate}\]
\[Q^{\text{Cou}} \quad \text{– energy thermalized via Coulomb interactions}\]
\[\xi_{CR} \quad \text{– primary CR ionisation rate}\]
\[Q^{CR} \quad \text{– energy thermalized via Coulomb interactions}\]
4. Other processes

**Ionisation heating**

FUV radiation ionises metals and the electrons heat the gas

\[ \Gamma_C = 1.602 \cdot 10^{-12} R_c^{ph} n_C \]

compared to higher energy ionisation, the FUV radiative transfer is more complicated due to dust (\( \tau_{UV} \)), H\(_2\) (\( s_{C,H_2} \)) and C (\( s_{C,C} \)) self-shielding, leading to an ionisation rate

\[ R_c^{ph} = s_{C,C} s_{C,H_2} \chi_0 \alpha_C e^{-\tau_{UV}} \]

\( \alpha_C \) – carbon ionisation rate
\( \chi_0 \) – strength of FUV radiation field
4. Other processes

H₂: a special case

H₂ is the most abundant molecule and its excitation and chemistry couple strongly to the radiation/thermal balance:

- H₂ can self-shield against photodissociation
- H₂ formation on dust leads to “hot” excited H₂ – H₂^{exc}
- H₂ absorbs FUV radiation (pumping) – H₂^{exc}
- H₂^{exc} de-excites through radiation or collisions or reacts chemically
4. Other processes

**H₂ heating**

**Dissociation heating:** kinetic energy of the H-atoms is \( \sim 0.4 \text{ eV} \) \cite{Stephens&Dalgarno1973}

\[
\Gamma_{\text{diss}} = 6.4 \cdot 10^{-13} R_{ph}^H n_{H_2}
\]

- \( R_{ph}^H \) – photodissociation rate of H₂ including dust and self-shielding
- \( R_{coll}^{H_2\text{exc}} \) – collisional de-excitation rate
- \( \Delta E \) – pseudo vibration level \( \sim 2.6 \text{ eV} \) (v=6)

**Collisional de-excitation:** kinetic energy of H₂ dissipated into the gas

\[
\Gamma_{\text{coll}} = \Delta E \cdot R_{\text{coll}}^{H_2\text{exc}\rightarrow H_2} \left( n_{H_2\text{exc}} - n_{H_2} e^{-\left(\frac{\Delta E}{kT}\right)} \right)
\]

\cite{Tielens&Hollenbach1985] cooling correction (collisional excitation)

[Stephens & Dalgarno 1973]
[Stephens & Dalgarno 1973]
[Tielens & Hollenbach 1985]
H$_2$ heating

**Formation heating:** the surface reaction is exothermic and the assumption of equipartition of energy leads to $E_{kin} \sim 1/3 E_{bind}$

\[ \Gamma_{form} = 2.39 \cdot 10^{-12} R_{H2} n_H \]

- $R_{H2}$ – formation rate of H$_2$ on dust grains
- $E_{bind}$ – H$_2$ binding energy 4.48 eV
- $n_H$ – number density of atomic hydrogen

[Black & Dalgarno 1976]
4. Other processes

Dust thermal accommodation

Inelastic collisions between gas and dust thermalize the two (can heat or cool the gas)

The influence of this process on the dust energy balance is usually neglected (however, see viscous heating later ...)

\[
\Gamma_{\text{acc}} - \Lambda_{\text{acc}} = 4 \cdot 10^{-12} \pi \left\langle a^2 \right\rangle n_{\text{dust}} n_{\text{H}} \alpha_{\text{acc}}(T_{\text{gas}}) \sqrt{T_{\text{gas}}} (T_{\text{dust}} - T_{\text{gas}})
\]

\[\text{dust surface area}\]

- \(\alpha_{\text{acc}}(T_{\text{gas}})\) – thermal accommodation coefficient, \(~0.1…0.5\)
- \(T_{\text{gas}}\) – gas temperature
- \(T_{\text{dust}}\) – dust temperature
- \(n_{\text{H}}\) – total hydrogen number density \((n_H + 2n_{H2})\)
- \(\left\langle a^2 \right\rangle\) – second moment of the dust size distribution \(n(a) \sim a^{-3.5}\)
4. Other processes

**Processes relevant in special cases**

- **Bremsstrahlung**: in a plasma electrons and ions scatter off one another producing a continuum from radio wavelengths up to $\approx kT$

- **Viscous heating**: accretion causes friction

$$\int \Gamma_{vis} \, dz = \frac{3GM_* M}{8\pi r^3} \left(1 - \sqrt{\frac{R_*}{r}}\right)$$

[D'Alessio et al. 1998]

- **Chemical heating/cooling**: exothermic chemical reactions convert chemical potential energies into heat and endothermic reactions consume internal kinetic energy (cooling)

$$\Gamma_{chem} = \sum_r R(r) \gamma_r^{chem} \Delta H_r$$

[Woitke et al. 2011]
Heating and Cooling Processes

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3. Line heating/cooling
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4. Other Processes
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5. Exercise
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   I. Planet forming disk

Inga Kamp, KROME summer school November 26 – November 28, 2018, Concepcion, Chile
Exercise

The typical hydrogen number density in the diffuse ISM is \( n_\text{H} = 1 \, \text{cm}^{-3} \), the radiation field is \( G_0 = 1 \), and the density of \( \text{C}^+ \) is \( n(\text{C}^+) = 5 \times 10^{-4} \, \text{cm}^{-3} \), \( n(\text{e}^-) = 10^{-2} \, \text{cm}^{-3} \). Assume that photoelectric heating is the main heating process and fine structure emission by the [CII] 158 \( \mu \text{m} \) is the dominant cooling process. Derive an estimate for the gas temperature using the two-level approximation for [CII].

\[
\Gamma_{PE} / n_\text{H} = 1.4 \times 10^{-26} G_0 \text{erg} / \text{s}
\]

Photoelectric heating rate per hydrogen atom

\[
k_{01}(\text{e}^-) \approx 1.5 \times 10^{-6} (T)^{-0.5} \, \text{cm}^3 \, \text{s}^{-1}
\]

\[
E_j / k \, (\text{K}) = 91.21 \quad g_j = 4 \quad j = 1
\]

\[
g_0 = 2 \quad \lambda_{10} = 157.74 \, \mu\text{m}
\]

\[
A_{10} = 2.4 \times 10^{-6} \, \text{s}^{-1}
\]
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Disks are layered structures: ionized/atomic, ion-molecules, molecules, ices

[PD database: van Dishoeck et al. 2006; Ly $\alpha$ up to 70-90% of $L_{\text{FUV}}$: Schindhelm et al. 2012]

5. Examples

Planet Forming Disk

Disks are layered structures: ionized/atomic, ion-molecules, molecules, ices

\[ \chi = 10^3 G_0 \quad n = 10^{12} \text{ cm}^{-3} \]
\[ \chi = 10^2 G_0 \quad n = 10^{10} \text{ cm}^{-3} \]
\[ \chi = 10^{-1} G_0 \quad n = 10^9 \text{ cm}^{-3} \]

Values at \( A_V = 1 \)

Dust properties in disks differ vastly from ISM

[PD database: van Dishoeck et al. 2006; Ly \( \alpha \) up to 70-90\% of \( L_{FUV} \): Schindhelm et al. 2012]


These are not classic PDRs, but live in a different parameter space!!!
5. Examples

Planet Forming Disk

shown is only the “dominant” process

Gas and dust couple efficiently below $A_V \sim I$

as soon as molecules form, gas cooling becomes very efficient

[DIANA standard T Tauri disk:
Woitke et al. 2016, Kamp et al. 2017]
Take away

• There is an overwhelming number of physical processes contributing to gas heating and cooling

• In many astrophysical regions (PDR, warm/cold neutral medium, hot ionized gas), only a subset of them dominate the energy balance – except planet forming disks that span a very wide range of conditions

• solving the energy balance of the dust requires knowledge of dust properties (composition, sizes), optical constants etc.

• solving the energy balance of the gas requires knowledge of atomic/molecular abundances, energy levels, line transitions ($\lambda$, $A_{ij}$), collisional cross sections for all relevant collision partners (often $e^-$, H, H$_2$) and knowledge of the dust (see above)