Physics and Chemistry of the Interstellar Medium

Carina Nebula by tthe Hubble space telescope
N. Smith and NASA/ESA. (16 pc size)

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Departament of *Molecular Astrophysics* at IFF-CSIC

OUTLINE of the LECTURE

1) Interstellar physics

ISM components
Heating and cooling
ISM 'phases' …

2) Atomic/Molecular excitation & radiative transfer

The equation of radiative transfer
Approximations and models …

3) Interstellar chemistry

Molecules in the ISM
Basic 'intro' to gas-phase chemistry
Public models...

Herschel's view of W3

Bibliography on Interstellar Medium (and credits to several slides)

* "Physical Processes in the Interstellar Medium"
  L. Spitzer, Jr., *New York: Wiley*, 1978.

* "Interstellar Chemistry"
  W.W. Duley and D.A. Williams, *Academic Press*, 1984.

* "The Physics and Chemistry of the ISM" and "Molecular Astrophysics"
  A.G.G.M. Tielens, *Cambridge University Press*, 2005 and 2021

* "Physics of the Interstellar and Intergalactic Medium"
  B. Draine, *Princeton University Press*, 2011.

* "Master in Astrochemistry"
  E. Van Dishoeck, 2010, Notes University of Leiden.

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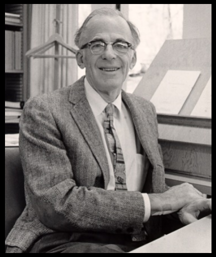

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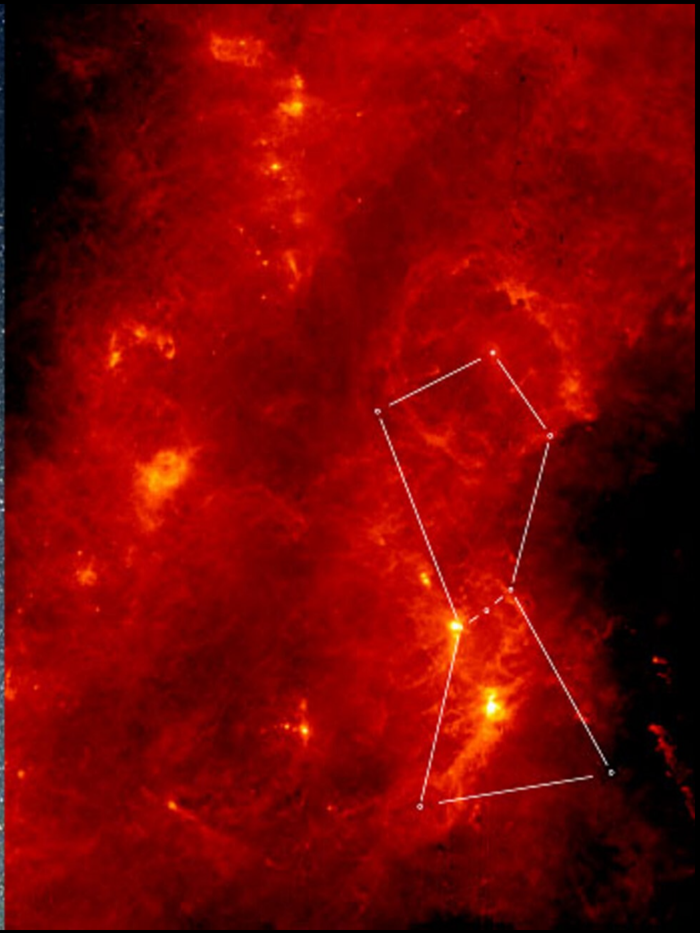
Orion in the visible

Hot stars and

ionized gas (nebular)

Orion in the visible

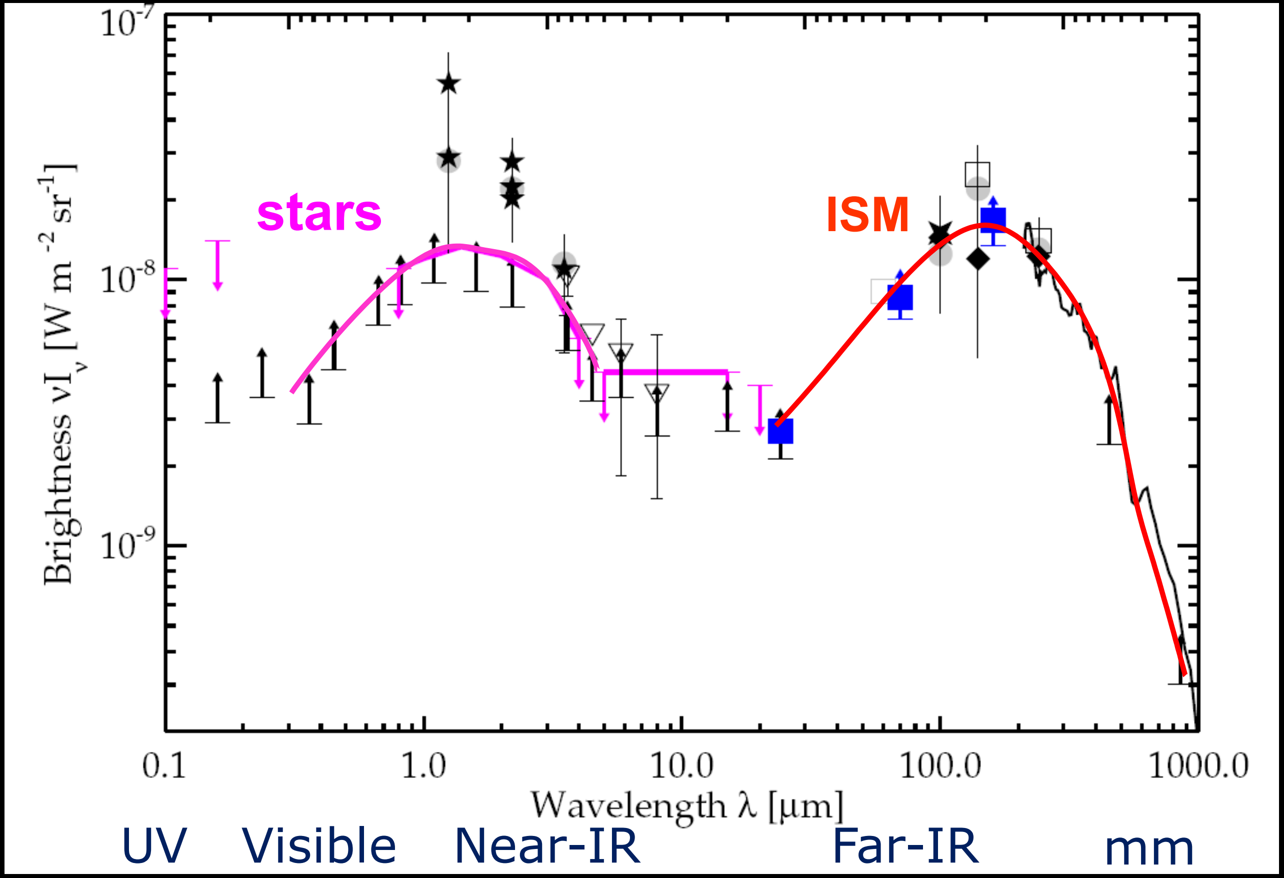
Far-IR dust emission



Hot stars and
ionized gas (nebular)

Cold ISM clouds

Half of the luminosity by the Universe is ISM dust (re)emission in the far-IR & submm



Starlight → ISM dust absorption → UV-heated dust re-emission

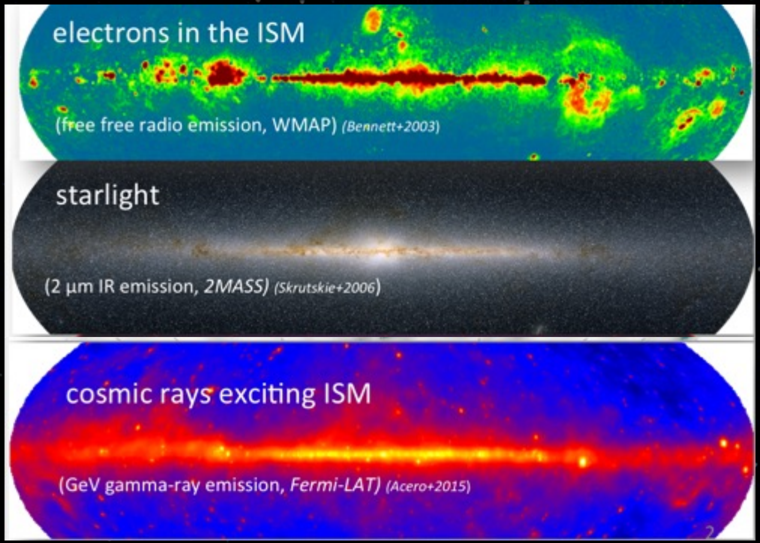
I. Interstellar Physics

Galaxies are nearly empty …

- Stars are separated by ≈2 pc (≈ 6.5 lyr)

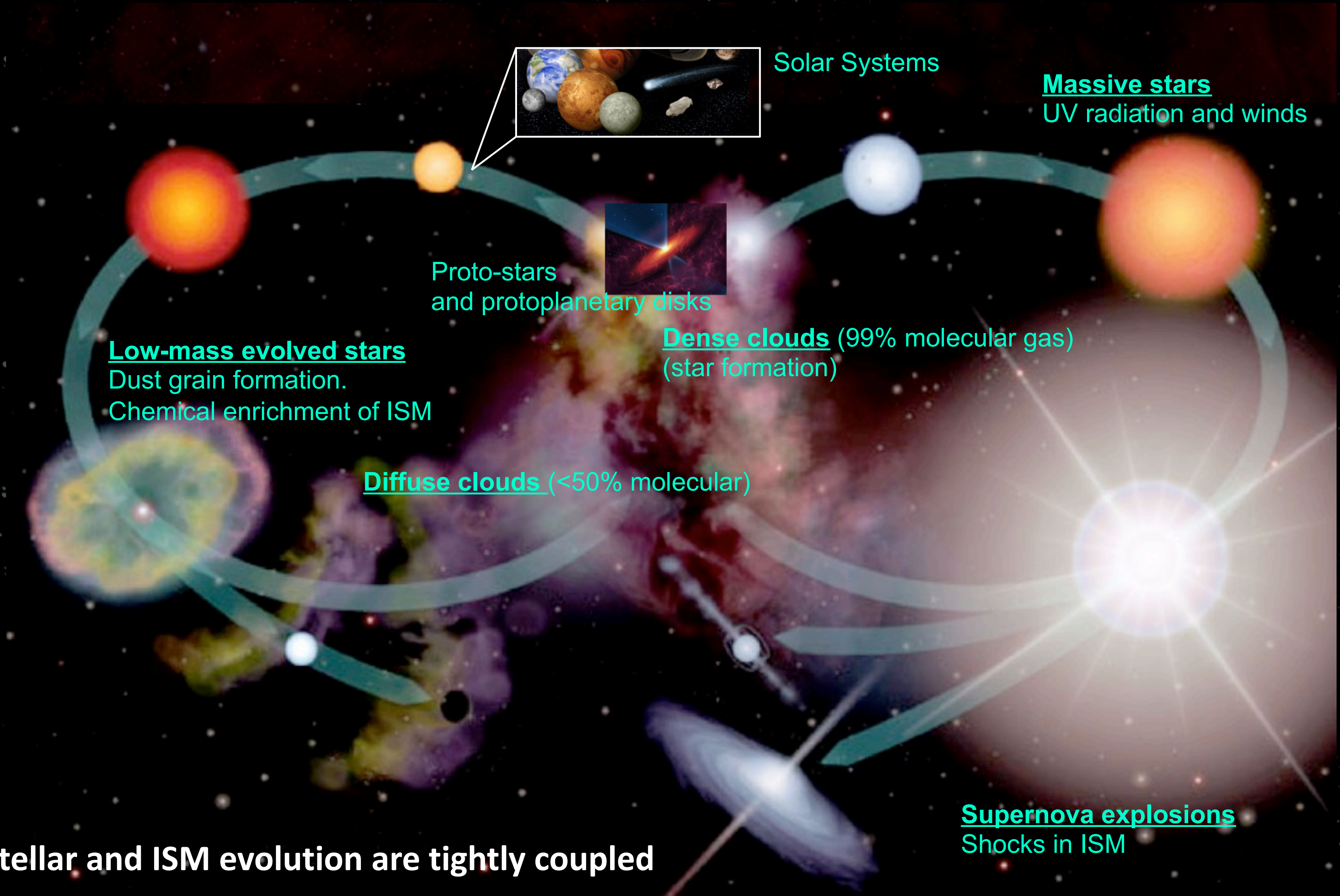
Interstellar Medium: *everything* between stars (matter, radiation, magnetic field …)

- **Gas**: atoms, molecules, electrons, …
- **Dust**: small solid grains, ≈ 0.1 μm in size, **~ 1% in mass wrt gas**
- **Cosmic rays** (particles): energetic protons, nuclei, and e^- (1 MeV to 10^{20} eV … ISM ~ GeV)
- **Radiation**: radio (plasmas), CMB (2.7 K), Far-IR to mm (dust thermal emission), VISIBLE and UV (starlight), X-rays (hot gas in shocks), γ-rays …



The **ISM** of the **Milky Way** as seen in **radio**, **IR**, and **γ-rays**

- As galaxies evolve, the ISM is slowly converted into new stars → **fuel for star formation**
- As stars die they return matter to the ISM → **chemical enrichment**
- 90 % of the baryons in the Milky Way are in stars ($\approx 5\cdot10^{10}\,M_{Sun}$) and **10% is in the ISM** ($\approx 7\cdot10^{9}\,M_{Sun}$)



Stellar and ISM evolution are tightly coupled

- **Stellar and ISM are tightly coupled** ← Stellar **UV**, **CRs** and **shocks** (*e.g.* winds and SNe) **heat** the ISM

- Most of the interstellar gas has temperatures and pressures ***close*** to be organized in "**phases**":

  1) **Cold Neutral Medium** (CNM): **diffuse HI** and **denser molecular** (H_2) **"CLOUDS"**

  2) **Warm Neutral Medium** (WNM) +Warm Ionized Medium (WIM) +Hot Ionized Medium (HIM)

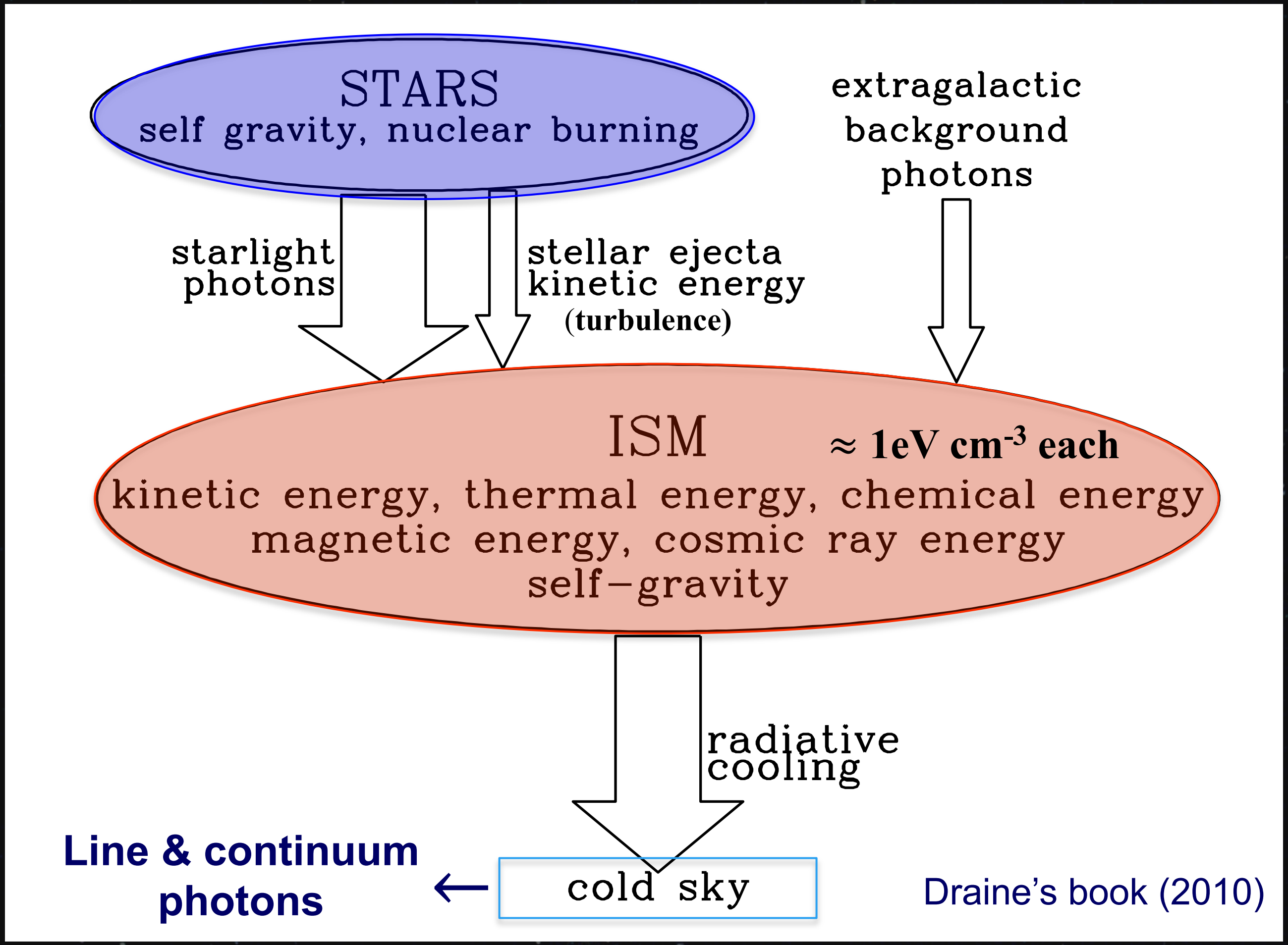
  → **"INTERCLOUD" component**

- These "phases" depend on how the gas is heated & cooled → **Microphysical processes !**
- Chemical composition **determines** how the gas is cooled → **Chemistry and spectrosocopy!**

SUMMARY: Much of the **ISM research** deals with understanding the (macro) **astrophysical processes** and also the **detailed microprocesses** that form, destroy, and excite atoms, molecules, and dust grains

Dust continuum emission Herschel/PACS & SPIRE (Molinari et al.)

Flow of Energy in normal Galaxies



CRUCIAL: Owing to very low gas densities and presence of UV, turbulence, and cosmic rays:
→ **ISM is NOT is equilibrium** → A single temperature DOES NOT describe all processes $T_k \neq T_{ex} \neq T_{ionization}$

→One needs to **study** and **balance all microprocesses** using their **specific rates and cross-sections**:
Thermal balance, **excitation & de-excitation**, **ionization & recombination …**

ISM "phases" in our Galaxy

H^+ (23% of mass) **HI** (60%) H_2 (17%)

Volume filling in the Milky Way

Phase	Density n_0^a (cm^{-3})	Temp. T^b (K)	Volume (%) ϕ_v^c (%)	Mass M^d (10^9 $M_\odot$)
Hot intercloud	0.003	10^6	~50.0	—
Warm neutral medium (WNM, HI)	0.5	8000	30.0	2.8
Warm ionized medium (H^+)	0.1	8000	25.0	1.0
Cold neutral medium[j] (CNM, HI & H_2)	50.0	80	1.0	2.2
Molecular clouds (SF, H_2)	>200.0	10	0.05	1.3
HII regions (H^+)	1–10^5	10^4	—	0.05

[a] Typical gas density for each phase.
[b] Typical gas temperature for each phase.

Tielens's book

~Pressure equilibrium

$P_{th} / k = n\,T$:

Field-Goldsmith-Habing+69 (CRs heating)
Dalgarno & McRay 72 (review)
Wolfire+95 (stellar FUV photons)

The volume filling factor scales inversely with the density:
most of the ***volume*** is in the **hot** & **warm** phases, most of the ***mass*** is in the **cold neutral** ISM phases

→ PROPERTIES, MASSES, FILLING FACTORS… VERY UNCERTAIN NUMBERS.
→ HARD TO GET A GLOBAL PICTURE OF THE **ISM OF GALAXIES** AS A WHOLE → on-going research…

The neutral ISM

Hydrogen is atomic (HI) or molecular (H_2) but not ionized (H^+)

Dense molecular clouds, diffuse clouds (CNM), inter-cloud (WNM)

Heating of the neutral interstellar gas

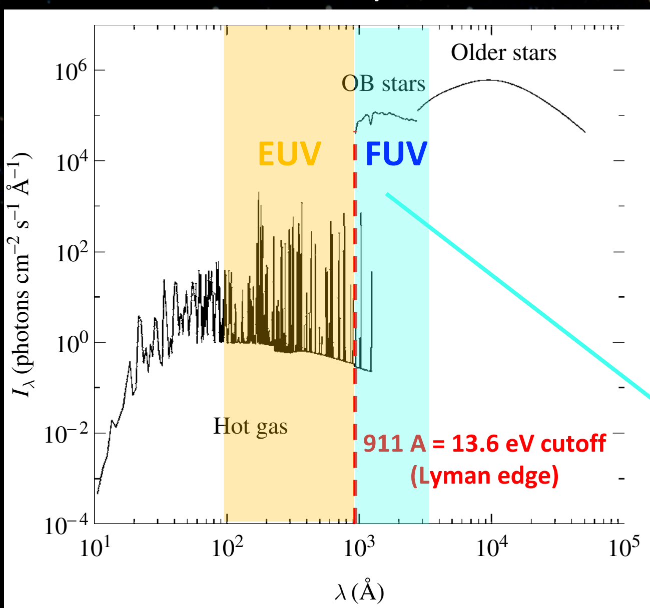
- **O- and B-type massive stars emit UV radiation fields:**

  - **Extreme-UV (EUV)** photons with **100 eV > $h\nu$ > 13.6 eV** ionize H → **HII regions & WIM**

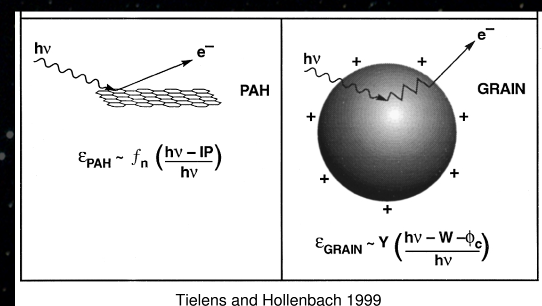
  - *Only* **far-UV (FUV)** photons with **$h\nu$ < 13.6 eV** propagate inside **neutral HI and H_2 clouds**

  IP(Hydrogen) = 13.6 eV; IP(Nitrogen) = 14.5 eV; IP(Carbon)=11.3 eV; IP(Sulfur)=10.4 eV

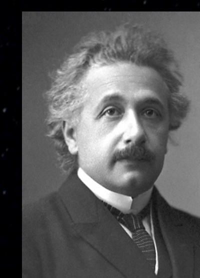
FUV photons impact dust grains and PAHs which eject energetic electrons through photo-electric effect → 'photo-electrons' collide with atoms and molecules and HEAT the gas



Interstellar Radiation field



Photoelectric Heating on PAHs and Grains



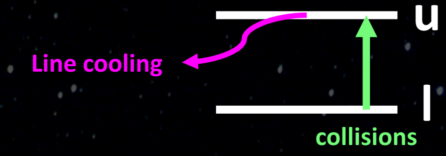
Nobel Prize
A. Einstein (1921)

G_0 = 1 Habing field = 10^8 FUV photons cm^{-2} s^{-1}

Examples: $G_0 \approx$ **1.7** in solar neighborhood (mean ISRF)
$G_0 \approx 10^{4-5}$ close to massive stars

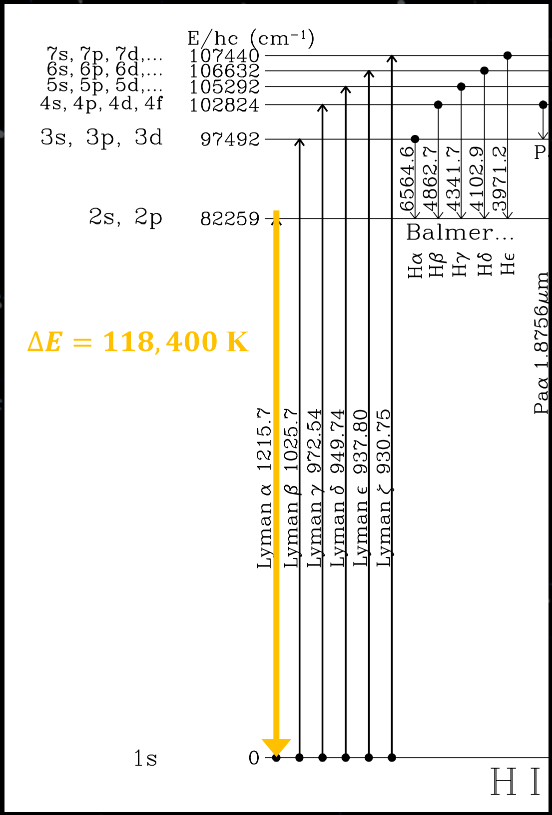
Cooling of the neutral interstellar gas

Ability of gas to cool itself *sets* the ISM “phases”

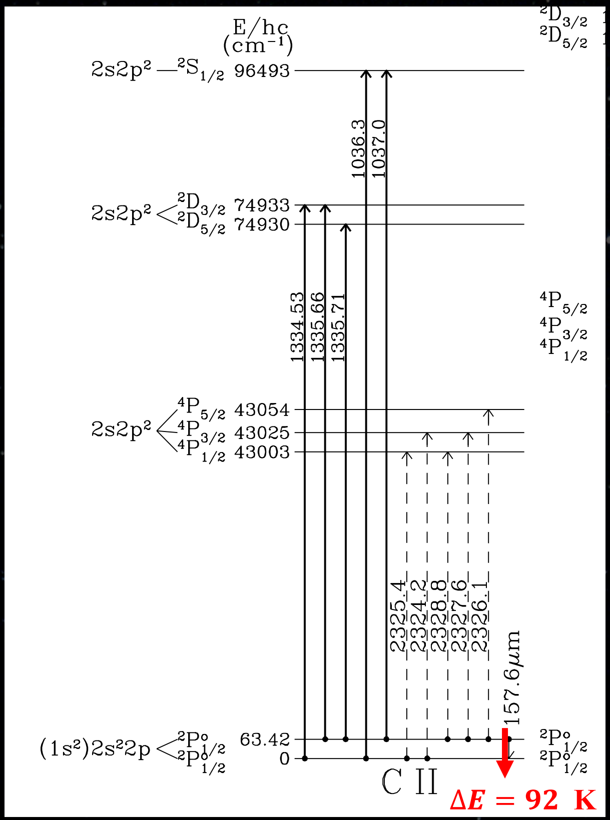


- **Collisions** of **HI** atoms, **C**$^+$ ions and **CO** molecules with photo-electrons (and H_2 inside molecular clouds) EXCITE the *lowest energy* available levels **(electronic, fine-structure, rotational)**
- **Emission of a line photon** - escaping the cloud **COOLS** the gas (**thermostats**!).

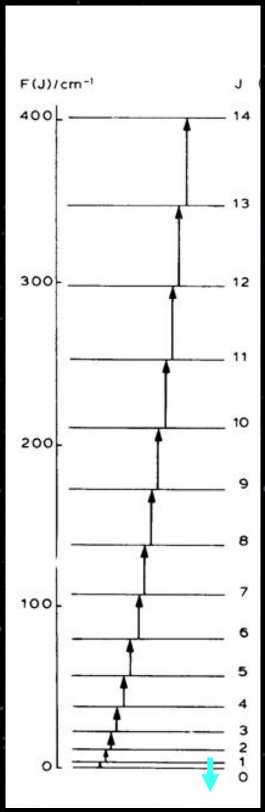
Ly α cooling (1216 A) of warm HI (WNM) ($T_{gas} \approx$ 8,000 K)



[CII] 158μm cooling of diffuse clouds (CNM) ($T_{gas} \approx$ 80 K)

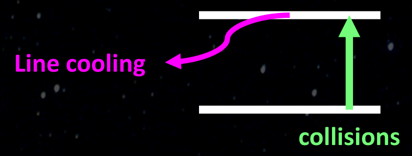


CO cooling of dense molecular gas ($T_{gas} \approx$ 10 K)



ΔE(J=1-0) = 5.5 K

Two-phases model of the neutral ISM



How do we determine T_{gas} ?

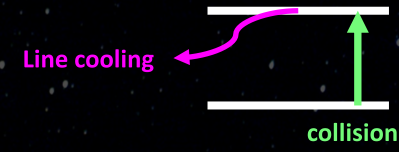
Thermal equilibrium → Heating = Cooling

$\Gamma = n\,\Lambda$ → gives T_{gas}

with n = gas density

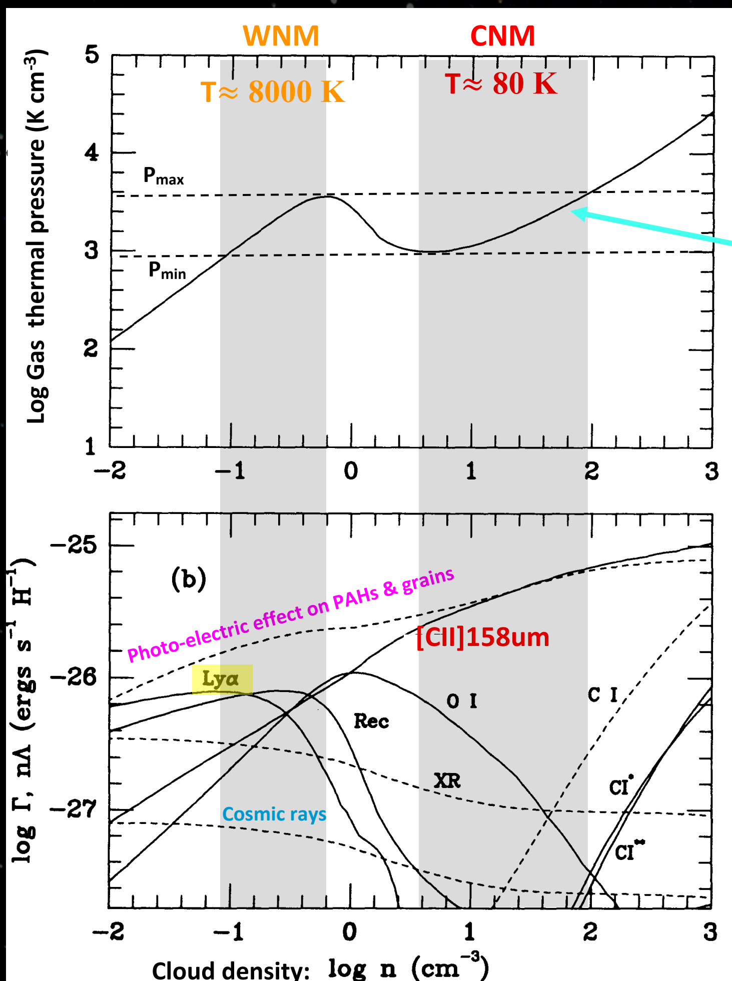
$P_{th}/k = n\,T_{gas}$ = gas thermal pressure

Two-phases model of the neutral ISM



Two-phases can exist in **thermal pressure equilibrium** with $\mathbf{P_{th}/k} = \boldsymbol{n\,T \approx 3000\ K\ cm^{-3}}$

"Thermally bi-stable"



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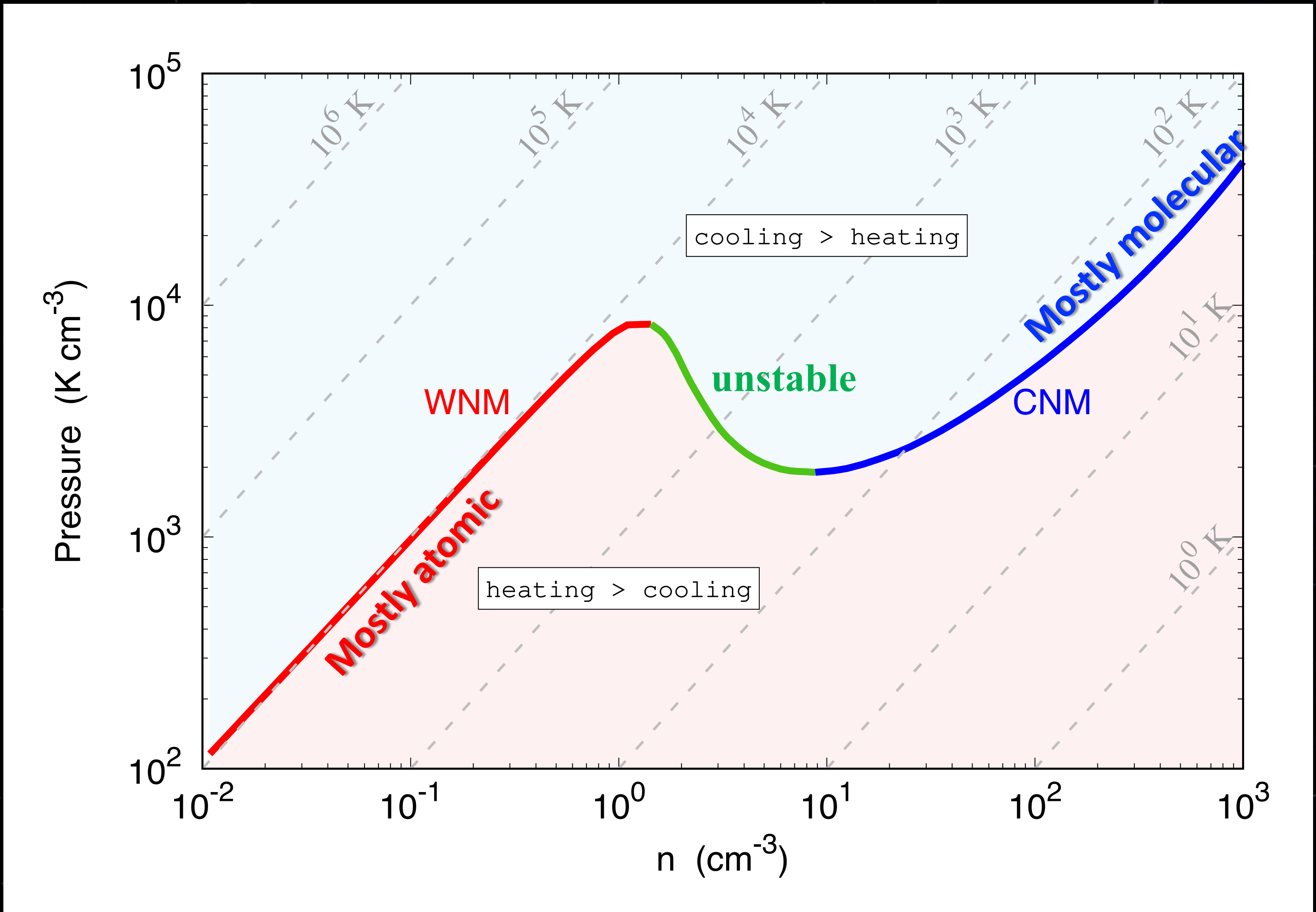
- - - - - - - **Heating processes**

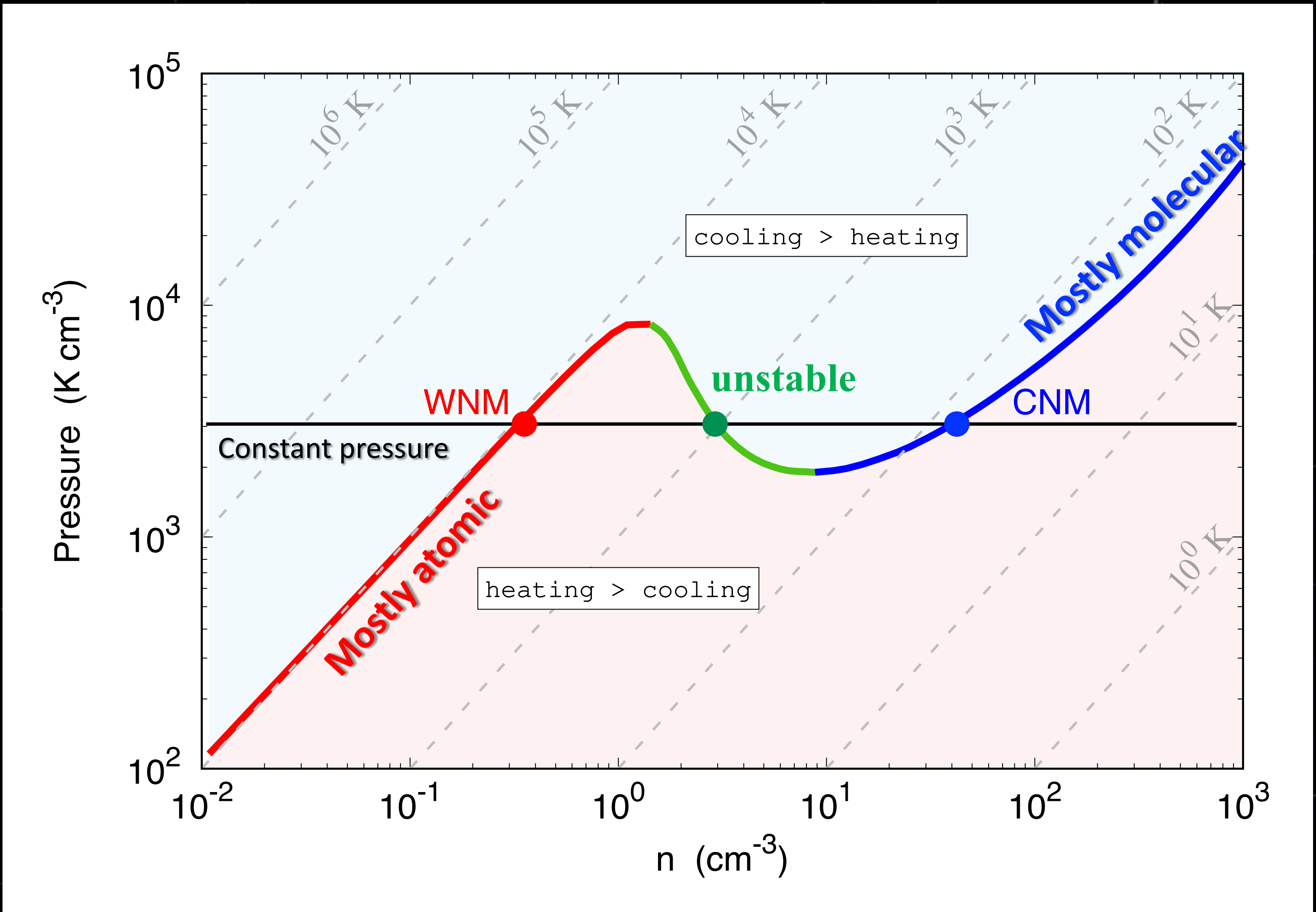
——— **Cooling processes**

Wolfire +1995, 2003



Thermal bi-stability of the diffuse neutral gas

Adapted from Godard+2024



Thermal bi-stability of the diffuse neutral gas

Adapted from Godard+2024

Dense molecular clouds

$n(H_2) > 10^3$ cm^{-3} M ~10^3-10^7 M_{sun} (those you see in CO & HCN emission with ALMA)

Dense molecular clouds are **self-gravitating** ($P_{tot} > P_{amb}$) rather than in pressure equilibrium with other phases in the ISM.

Cosmic Ray heating dominates

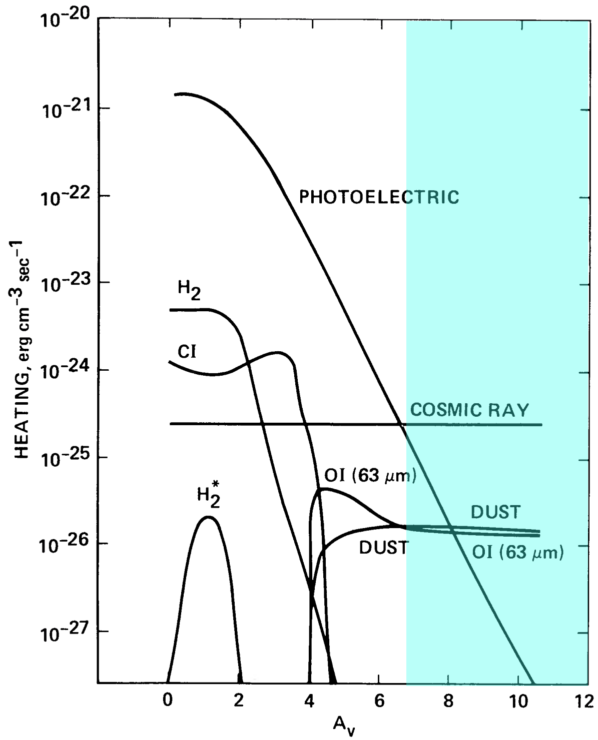


FIG. 1.—Different gas heating terms in the energy balance for the standard model, given as a function of the visual extinction A_v into the cloud. "Photoelectric" refers to the grain photoelectric heating mechanism; "H_2" refers to photodissociation of H_2; "H_2^*" is the collisional de-excitation of FUV–pumped H_2^*; "C I" is the photoionization of atomic carbon; "O I (63 μm)" is the collisional de-excitation of IR-pumped neutral oxygen; "dust" refers to the collisions with warm dust.

Hollenbach +1991

CO line cooling dominates → T_k = 10-20 K

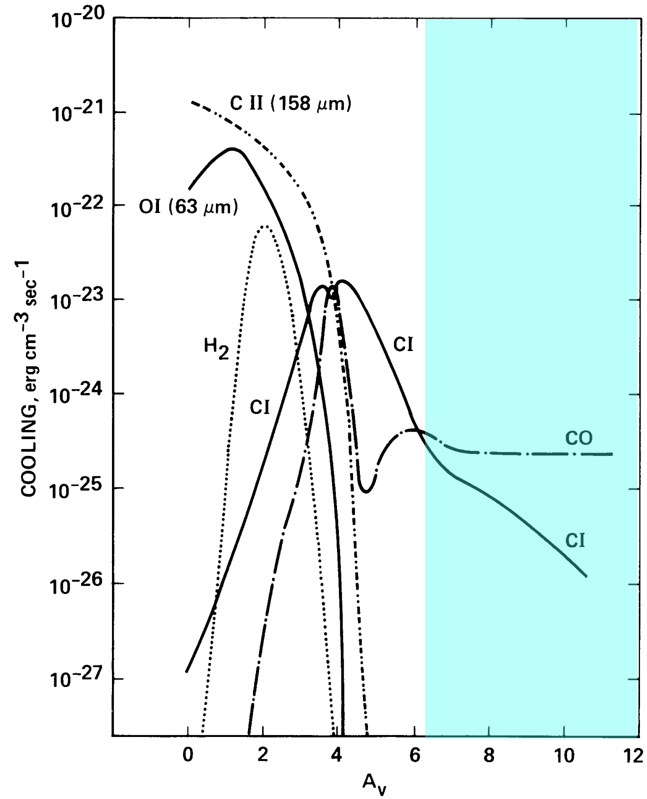
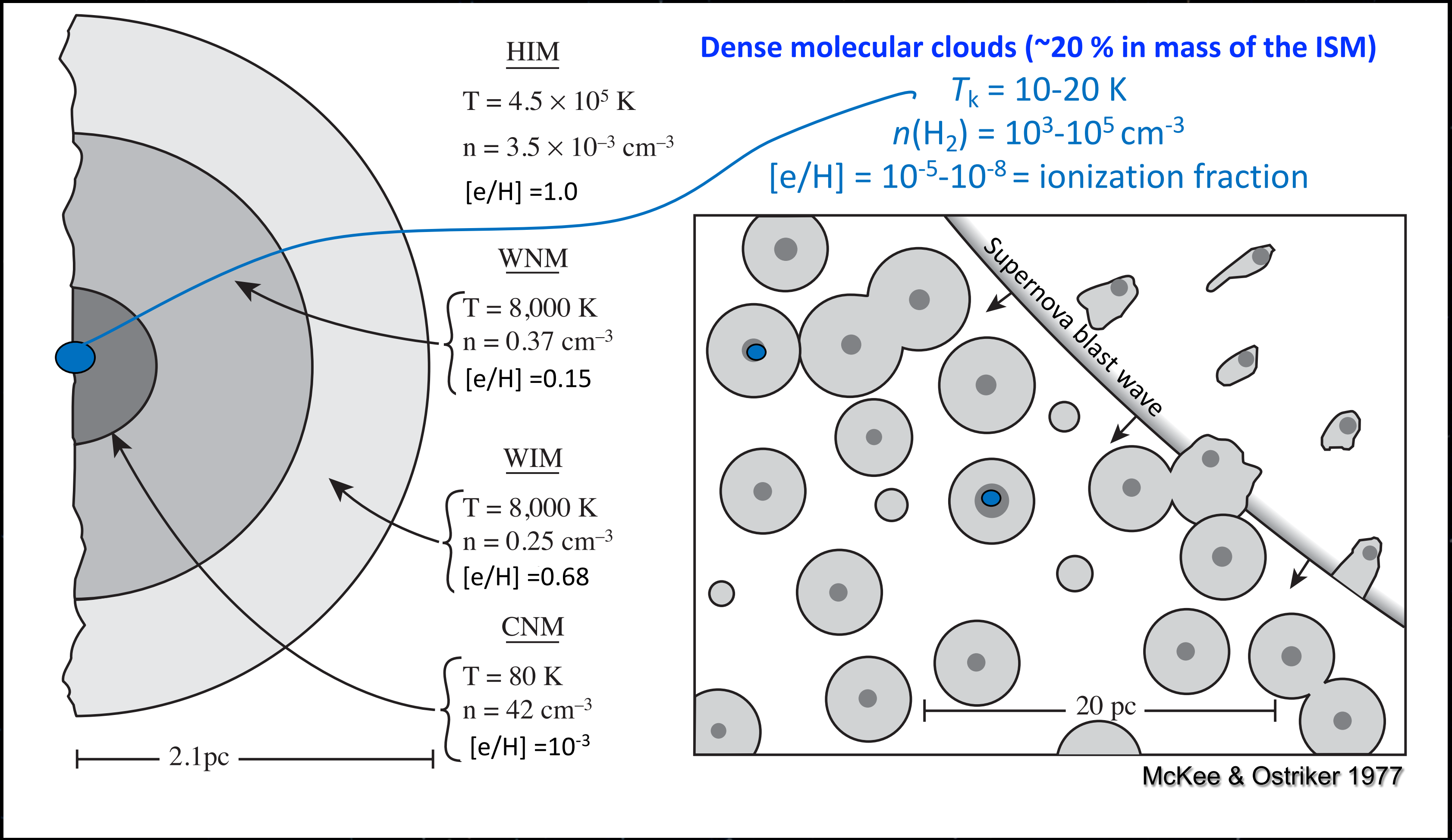


FIG. 2.—Different gas cooling terms in the energy balance for the standard model, given as a function of the visual extinction A_v into the cloud. "C I" is the sum of [C I] 370 μm and [C I] 609 μm; "H_2" and "CO" are the total cooling by rotational and vibrational transitions of these molecules.

The *classical* multi-phase model of the ISM

cloud = CNM **inter-cloud medium** = WNM and WIM + HIM



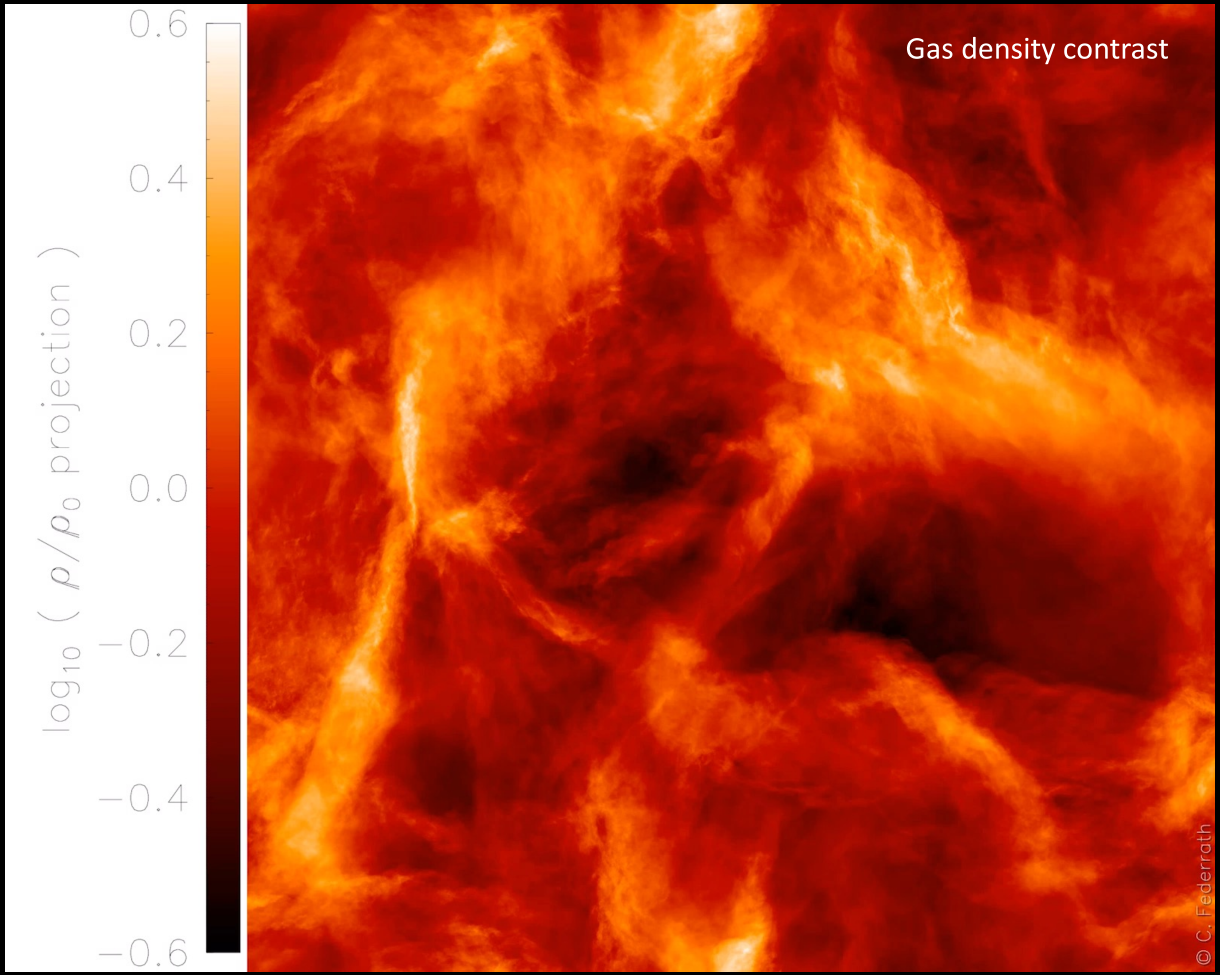
But the ISM is ***dynamic*** & ***turbulent …*** changes of 'phase' or 'mixing' occur, observations show WNM **HI clouds in the thermally unstable regime** ($T \neq 8000$ K), etc.

Today: hydrodynamic simulations of the turbulent (+ shocks) and magnetized ISM

Modern-day simulations of the turbulent ISM

Complicated problem: **turbulence is injected at very large scales but dissipated a very small scales**

Hennebelle & Falgarone 2012 for a *review.*



Shocks can induce phase transitions between WNM and CNM

Godard+2024

Turbulence in molecular clouds can be supersonic → shocks…

Federrath et al. 2021,

Nature Astronomy, **FLASH Code**

Supersonic to sonic turbulence transition at ~0.1 pc (gravity overcomes turbulence. *e.g.,* P. André+2010)

Interstellar extinction by ISM dust

For **standard** diffuse ISM grains in the Milky Way:

$$N_H = N(H) + 2N(H_2) \approx 1.9 \cdot 10^{21} \cdot A_V \;\; \mathrm{cm^{-2}\,mag^{-1}}$$

Bohlin et al. (1978, *ApJ*)

- A_V = magnitudes of **extinction in the visible range** (V= λ_V = 0.55 µm = 5500 Armstrongs) …

A_V defines a useful "scale" **to classify ISM neutral clouds**:

* $A_V \leq 1$ mag → "***Diffuse cloud***" : Visible- and FUV photons from stars are not attenuated

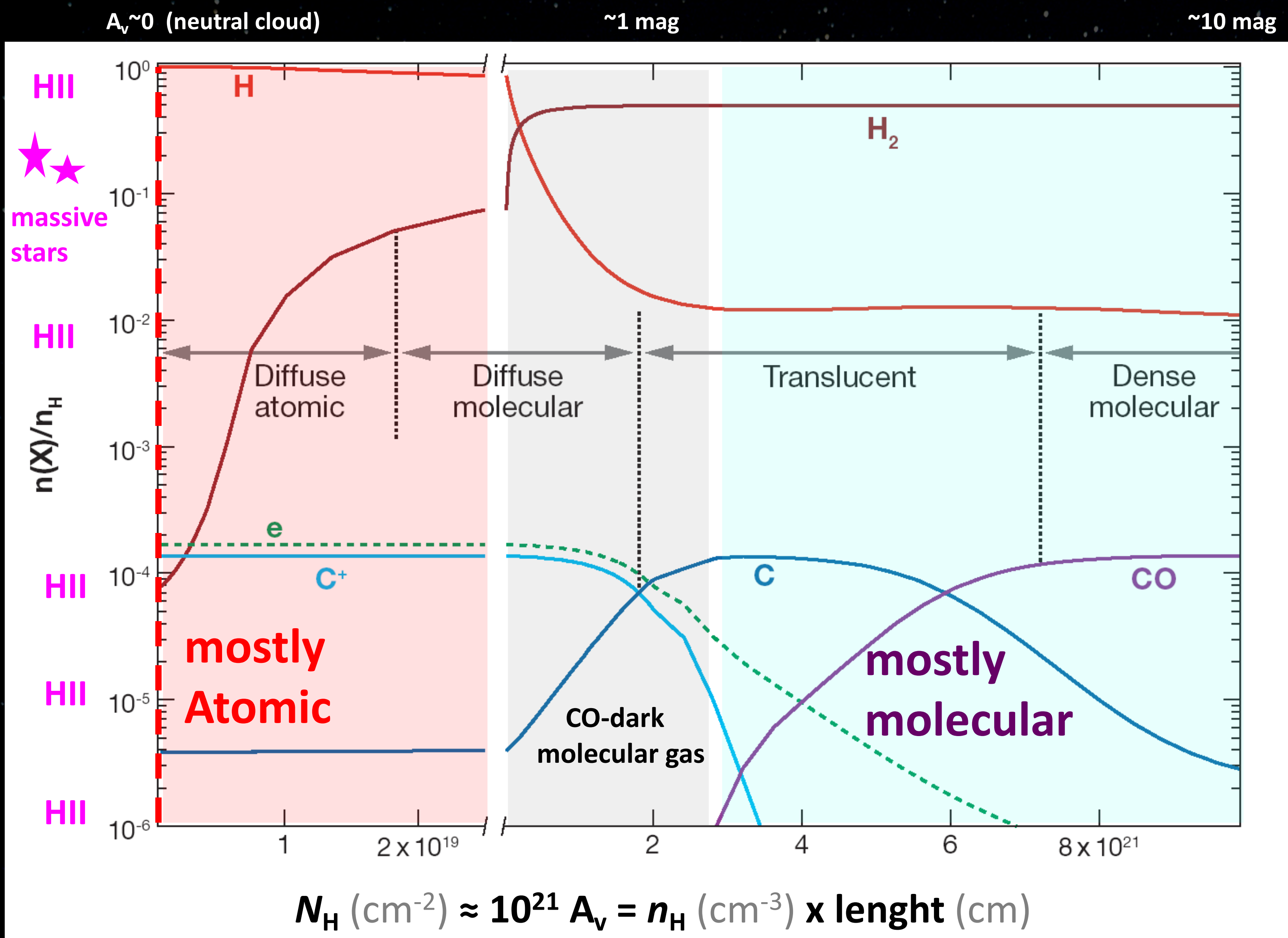
  → gas is neutral but large fraction of hydrogen is in HI atoms

* $1 \leq A_V \leq 4$ mag → "***Translucent molecular cloud***": FUV flux is still significant

  → most hydrogen is molecular H_2

* $A_V > 4$ mag → "***Dense Molecular cloud***": mostly shielded from stellar FUV radiation

Model of the neutral ISM



Only E < 13.6 eV photons penetrate neutral clouds → far-UV photons, below Lyman limit (λ > 911 A)

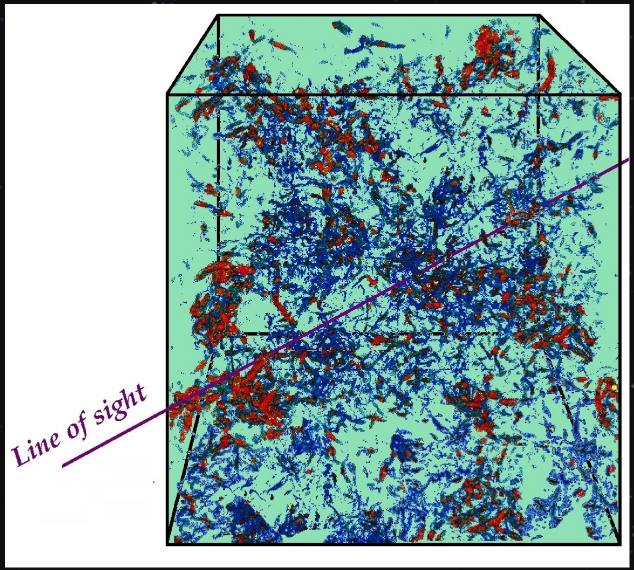
Remember, IP(Carbon) = 11.3 eV

Open big questions

- How are ISM clouds **assembled from diffuse gas** and **how do they ultimately form** stars?

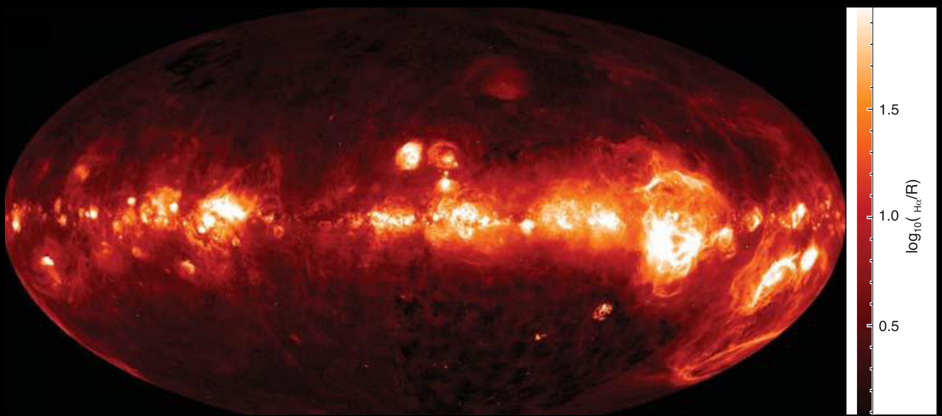
- How do the different **energy sources** (UV, thermal, CRs, turbulence, magnetic fields, gravity) contribute to the dynamical properties and evolution of the ISM ? **Feedback processes?**

- What are the limits of chemical complexity in the ISM ? → How are molecules formed?
  What do different molecules trace?



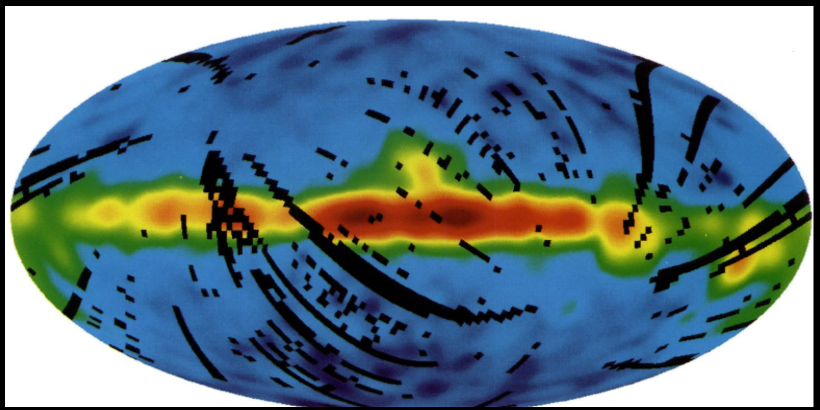
Answers: Observations and models !

Hα survey WIM



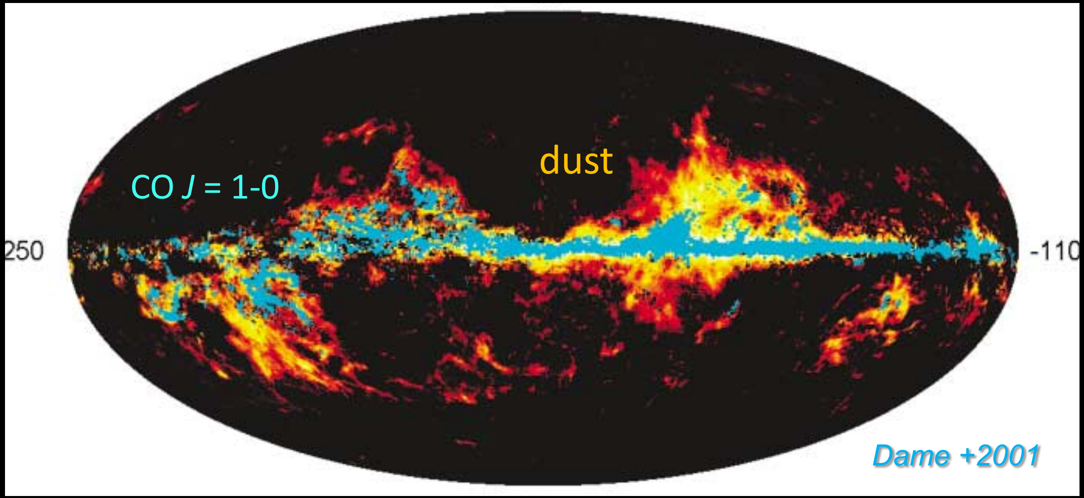
Finkbeiner +2003

[CII]158μm (C^+) Most important coolant of the CNM



Bennett +1994, COBE

Molecular ISM

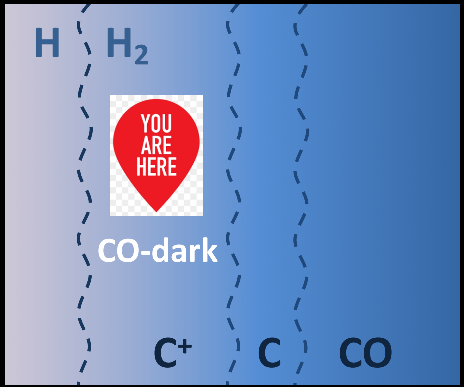


Dame +2001

Excess of dust emission over CO and HI column density

Planck collaboration+11 (*dust*) & Grenier+15 (*γ-rays*)

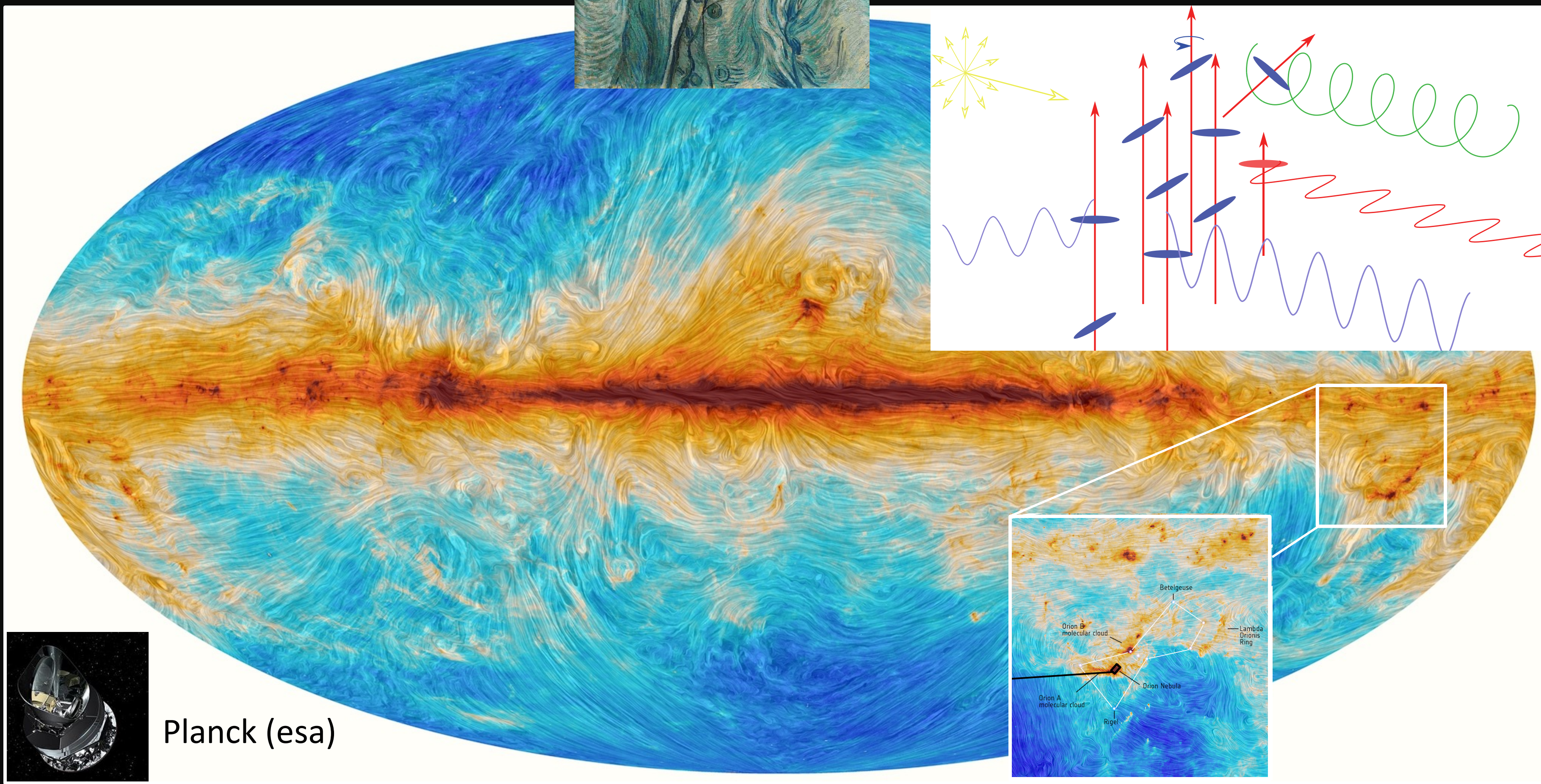
→ **Missing baryons 20-80% of molecular gas in galaxies?**



Magnetic field

Wavelength-dependent polarization of light
→ **grains are not spherical**

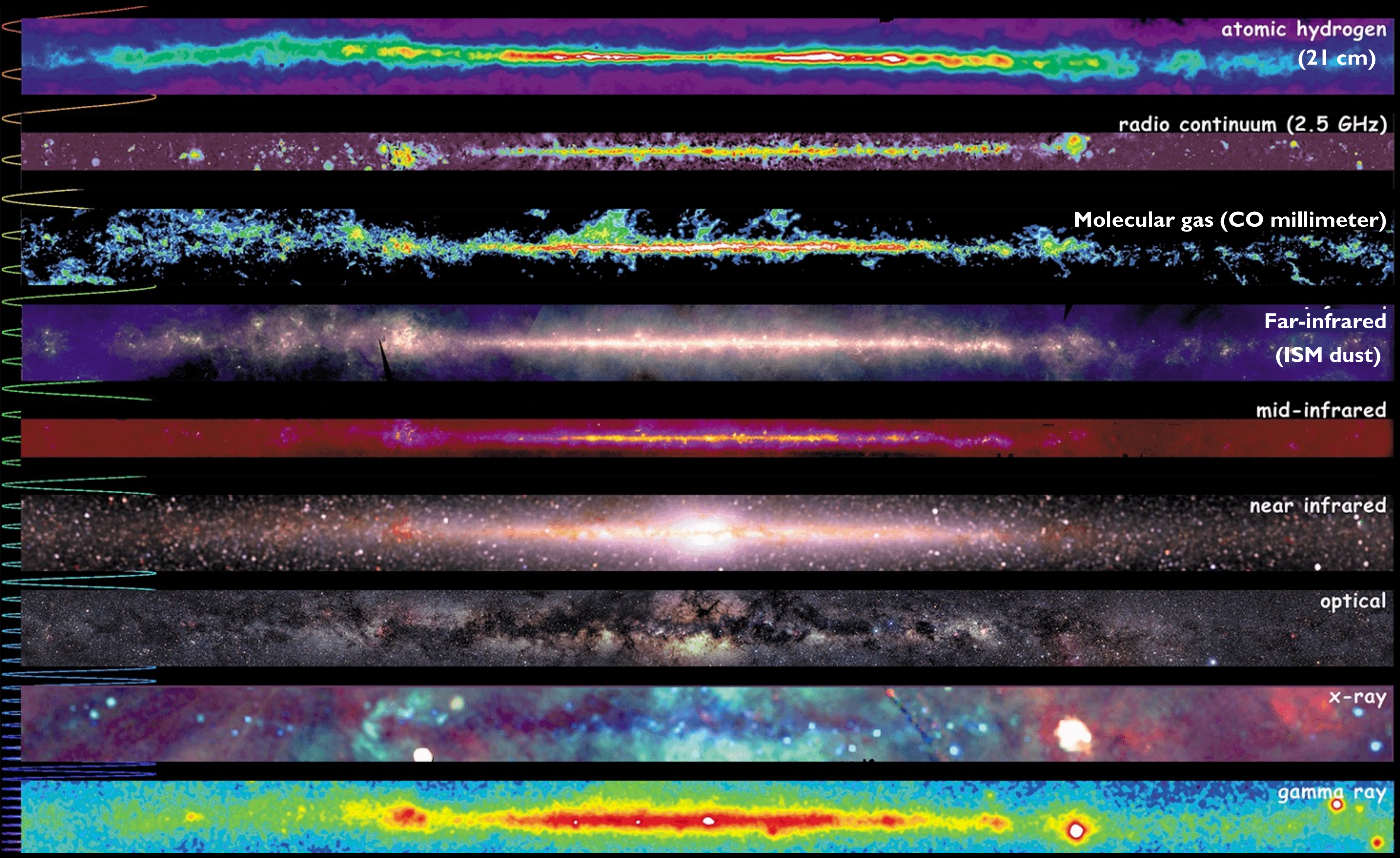
If polarization degree and angle are measured
→ **B field orientation can be estimated.**



Planck (esa)

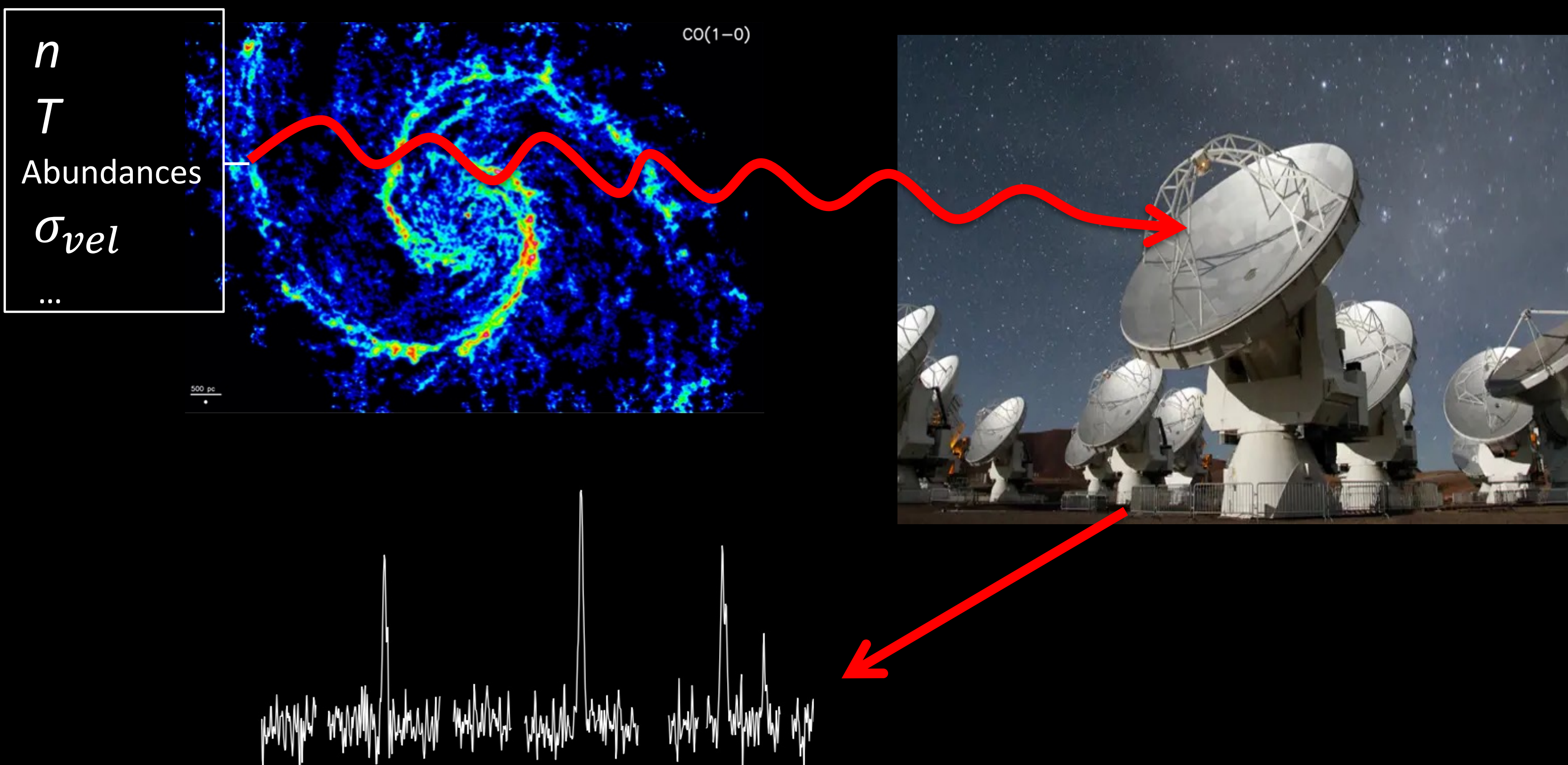
Sub(mm) dust thermal emission and polarization **Magnetic field orientation (texture)**

Most λ's carry specific information about the ISM



The Milky Way at kpc scales

II. Atomic/Molecular excitation and radiative transfer



The equation of radiative transfer

I_ν = energy time^{-1} area^{-1} frequency^{-1} solid angle^{-1} = erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

defining **τ_ν** and **S_ν** as:

$$d\tau_\nu = \alpha_\nu\, ds \qquad S_\nu = \frac{j_\nu}{\alpha_\nu}$$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

s path length of propagation of ray (=) cm

α_ν local absorption coefficient (=) cm^{-1}

j_ν local emission coefficient (=) erg s^{-1} cm^{-3} Hz^{-1} sr^{-1}

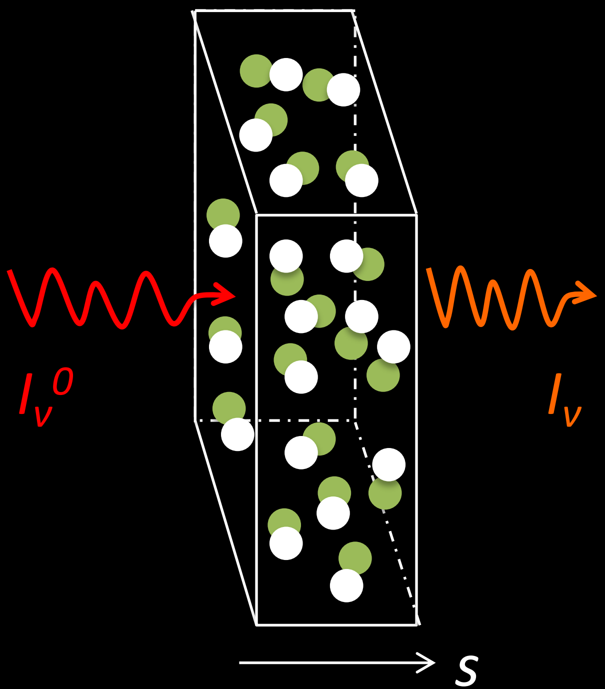
$1/\alpha_\nu$ ~mean free path (=) cm

Formal solution of the equation of radiative transfer:

$$I_\nu(\tau_\nu) = I_\nu^0\, e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu(\tau_\nu')\, e^{-(\tau_\nu-\tau_\nu')}\, d\tau_\nu'$$

Solution for an homogeneous medium:

$$I_\nu = I_\nu^0\, e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu})$$

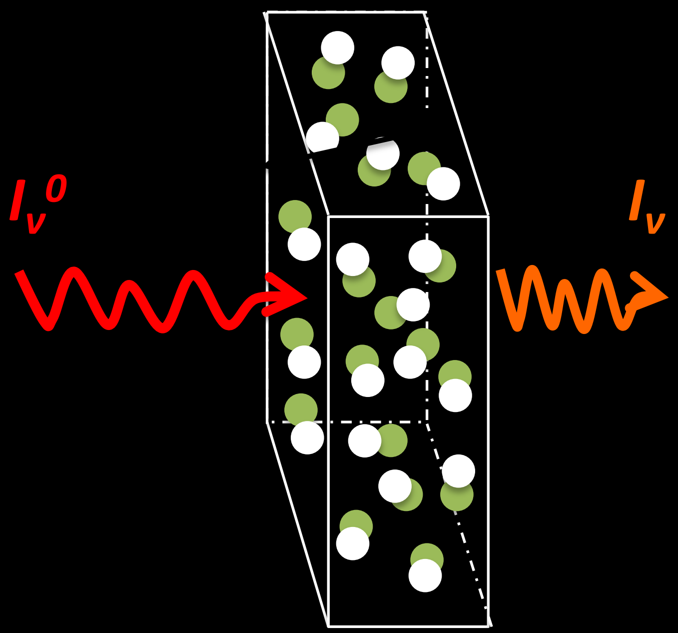


Limiting cases (τ_ν)

radiative transfer equation
for an homogeneous medium

$$I_\nu = I_\nu^0\, e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu})$$

→ It shows the effects of matter on radiation.



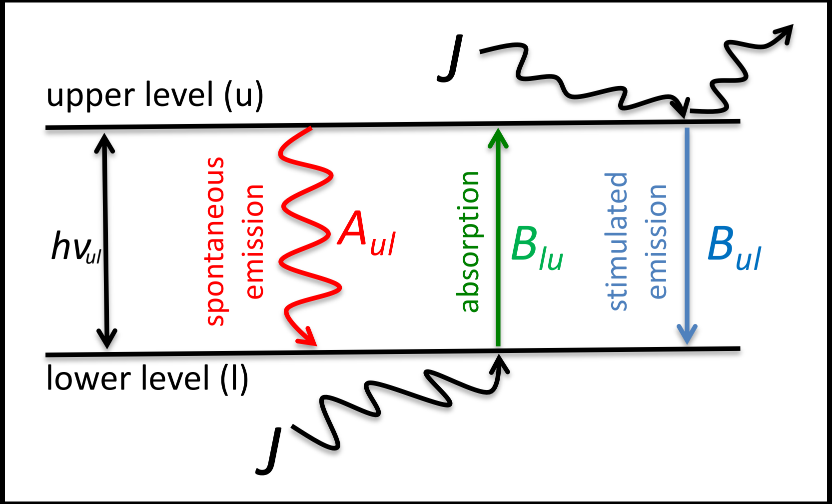
$\tau_\nu \rightarrow 0$ ➔ $I_\nu = I_\nu^0 + [S_\nu - I_\nu^0]\,\tau_\nu$ **optically “thin” emission**

$\tau_\nu \rightarrow \infty$ ➔ $I_\nu = S_\nu$ **optically “thick” emission**

From macroscopic (α_ν , j_ν) to microscopic quantities

two-level system

A_{ul}	***spontaneous emission** rate*	$[=]\ s^{-1}$
$J \cdot B_{lu}$	***absorption** rate*	$[=]\ s^{-1}$
$J \cdot B_{ul}$	***stimulated emission** rate*	$[=]\ s^{-1}$



Relations between Einstein coefficients

$$A_{ul} = \frac{2h\nu^3}{c^2} B_{ul} \quad (s^{-1}) \qquad g_l\, B_{lu} = g_u\, B_{ul}$$

$g_l\ g_u$ *statistical weight of lower and upper level*

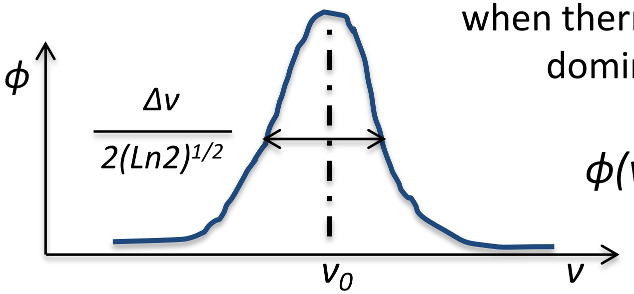
Average intesity J (over angle and line profile):

$$J = \frac{1}{4\pi} \int_{4\pi} d\Omega \int_0^\infty I_\nu\, \phi(\nu)\, d\nu$$

Intrinsic line profile function $\phi(\nu)$ in terms frequency $[=]\ Hz^{-1}$

normalized such as:

$$\int_0^\infty \phi(\nu)\, d\nu = 1$$



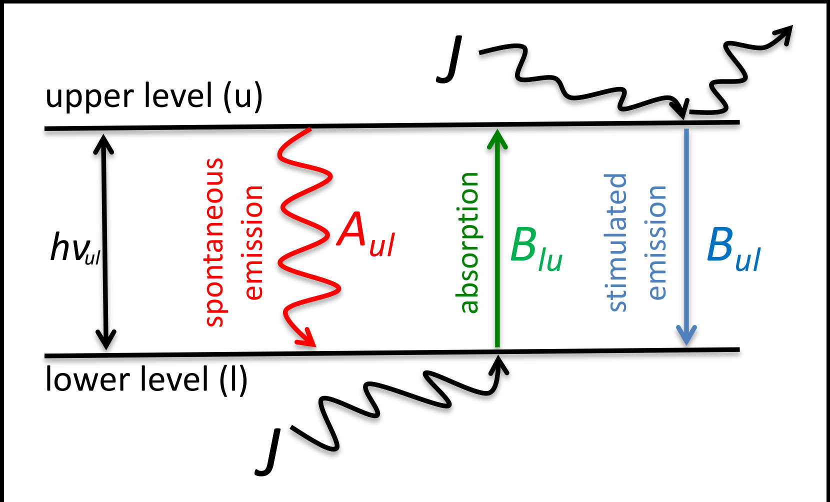
when thermal motions or microturbulence dominate → gaussian line profile

$$\phi(\nu) = \frac{1}{\Delta\nu\, \pi^{1/2}} \exp\left\{-\left(\frac{\nu-\nu_0}{\Delta\nu}\right)^2\right\}$$

From macroscopic (α_ν , j_ν) to microscopic quantities

$$j_\nu = \frac{h\nu}{4\pi} \, n_u A_{ul} \, \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu}{4\pi} \, (n_l B_{lu} - n_u B_{ul}) \, \phi(\nu)$$



j_ν emission coefficient (=) erg s^{-1} cm^{-3} Hz^{-1} sr^{-1}

α_ν absorption coefficient (=) cm^{-1}

A_{ul} Einstein coefficient of spontaneous emission [=] s^{-1}

B_{ul} and B_{lu} Stimulated emission/absorption coefficients [=] cm^{+2} erg^{-1} s^{-1}

g_l g_u Statistical weight of lower and upper level

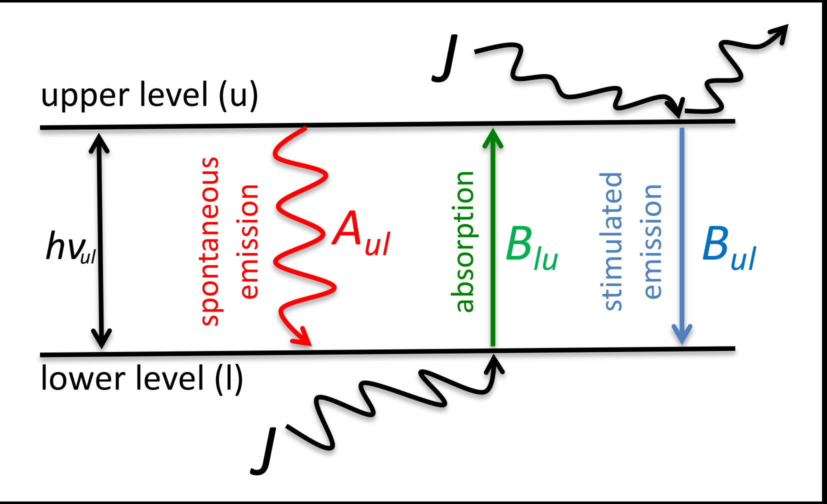
$\phi(\nu)$ Line profile function [=] Hz^{-1}

n_l n_u Population of lower and upper level [=] cm^{-3}

The excitation temperature

$$j_\nu = \frac{h\nu}{4\pi} \; n_u A_{ul} \, \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu}{4\pi} \; (n_l B_{lu} - n_u B_{ul}) \, \phi(\nu)$$



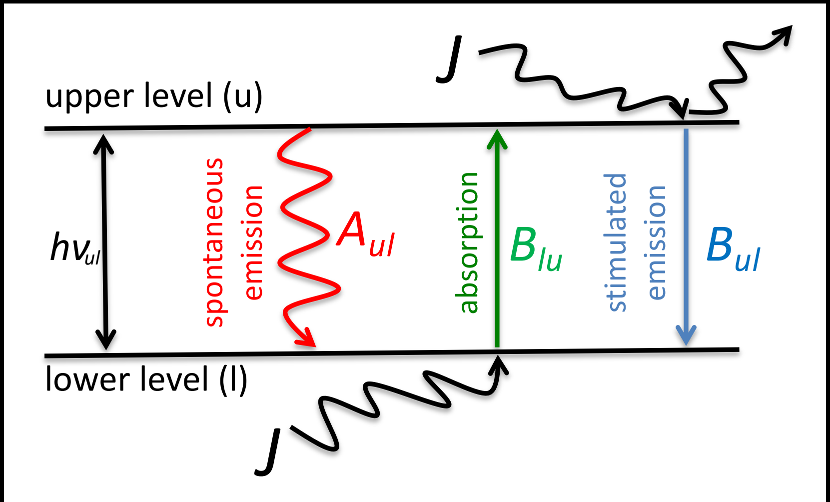
we define T_{ex} as in Boltzmann law $\quad \frac{n_u/g_u}{n_l/g_l} = exp(-h\nu/kT_{ex})$

$n_l/g_l > n_u/g_u$ ➔ $T_{ex} > 0$ ➔ $\alpha_\nu > 0$ ➔ $\tau_\nu > 0$ — "normal" populations **thermal emission**

$n_u/g_u > n_l/g_l$ ➔ $T_{ex} < 0$ ➔ $\alpha_\nu < 0$ ➔ $\tau_\nu < 0$ — inverted populations **maser emission**

The Source function S_ν

$$I_\nu = I_\nu^0\, e^{-\tau\nu} + S_\nu(1 - e^{-\tau\nu})$$



$$j_\nu = \frac{h\nu}{4\pi}\; n_u A_{ul}\, \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu}{4\pi}\; (n_l B_{lu} - n_u B_{ul})\, \phi(\nu)$$

$$\frac{n_u/g_u}{n_l/g_l} = \exp(-h\nu/kT_{ex})$$

$$S_\nu = \frac{j_\nu}{\alpha_\nu} = \quad \ldots \quad = \frac{2h\nu^3}{c^2}\, \frac{1}{\exp(h\nu/kT_{ex}) - 1}$$

Planck law at $T = T_{ex}$

Blackbody at T_{ex}

$$S_\nu = B_\nu(T_{ex})$$

But T_{ex} is not known …

Brightness temperature, $h\nu \ll kT$

radiative transfer equation
for an homogeneous medium

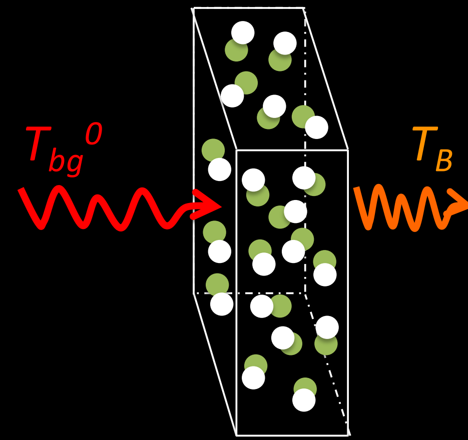
$$I_\nu = I_\nu^0 \, e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu})$$

When $h\nu \ll kT$ we can use the Rayleigh–Jeans law:

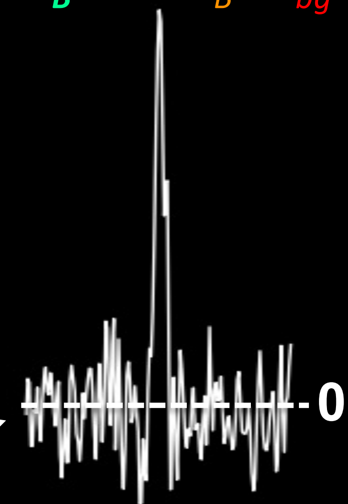
$$T_b = \frac{I_\nu c^2}{2k\nu^2}$$

Expanding the Planck law for small *hν*/k values …

$$T_B = T_{bg}^0 \, e^{-\tau_\nu} + T_{ex} (1 - e^{-\tau_\nu})$$



$T_B^{LINE} = T_B - T_{bg}^0$



ON – OFF measurement

$$T_B^{LINE} = T_B - T_{bg}^0 = (T_{ex} - T_{bg}^0) \cdot (1 - e^{-\tau_\nu})$$

$\tau_\nu \to 0$ ➔ $T_B^{LINE} \sim (T_{ex} - T_{bg}^0) \cdot \tau_\nu \sim T_{ex} \cdot N$ **optically 'thin' emission**

$\tau_\nu \to \infty$ ➔ $T_B^{LINE} \sim T_{ex} - T_{bg}^0 \sim T_{ex}$ **optically 'thick' emission**

How are level populations (n_u n_l) - **thus T_{ex} -   determined?**

Rotational population diagram
(or 'Boltzmann plot')

Hands-on Project 3: *Tracing the physical properties of warm molecular gas through observations and models of the submillimeter CO rotational ladder*

Wait until Thursday…

Statistical equilibrium equations

$$\frac{dn_i}{dt} = \sum_{j\neq i} n_j (J\cdot B_{ji} + \Upsilon_{ji} n) + \sum_{j>i} n_j A_{ji} - n_i \sum_{j\neq i} (J\cdot B_{ij} + \Upsilon_{ij} n) - n_i \sum_{j<i} A_{ij} = 0$$

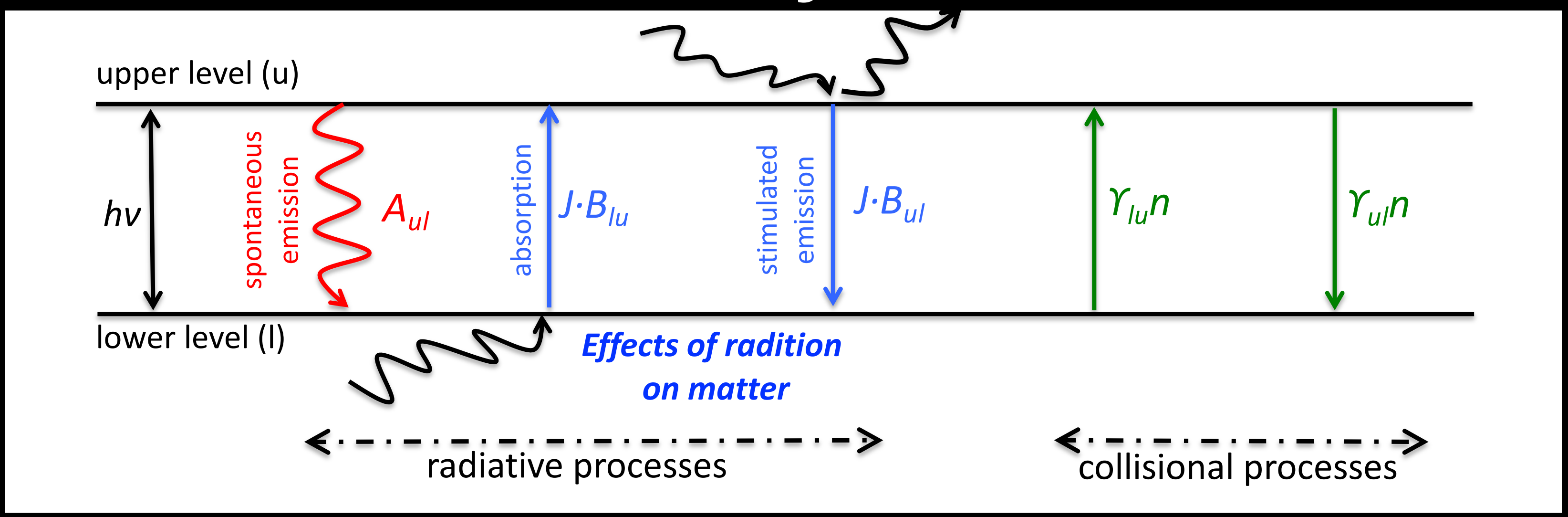
Populate upper level i — De-populate upper level i

Υ_{ul} *collisional rate coefficient for transition u → l* [=] $cm^3 s^{-1}$

n *colliders density (H_2, e^-, …)* [=] cm^{-3}

$\Upsilon_{ul}\cdot n$ *collisional excitation rate for transition u → l per unit time* [=] s^{-1}

Two-level system



Limiting case: collisional rates >> radiative rates → LTE

$$\frac{dn_i}{dt} = \sum_{j\neq i} n_j(\cancel{J B_{ji}} + \Upsilon_{ji} n) + \cancel{\sum_{j>i} n_j A_{ji}} - n_i \sum_{j\neq i}(\cancel{J B_{ij}} + \Upsilon_{ij} n) - \cancel{n_i \sum_{j<i} A_{ij}} = 0$$

$\Upsilon_{lu}\, g_l = \Upsilon_{ul}\, g_u \exp(-h\nu/kT_{kin})$ collisional rate coefficients must fulfil detailed balance

$$n_u \Upsilon_{ul}\, n - n_l \Upsilon_{lu}\, n = 0 \quad \rightarrow \quad \frac{n_u/g_u}{n_l/g_l} = \exp(-h\nu/kT_{kin})$$

"LTE" Boltzmann population distribution at T_{kin}

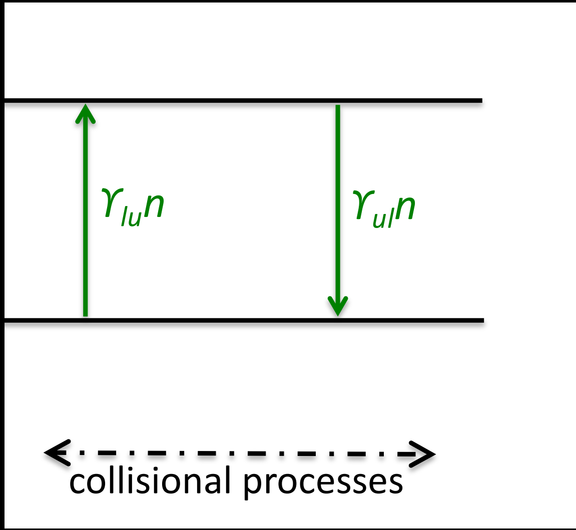
Collisional rate coefficients (e.g. $CO + H_2$):

$$\gamma_{ul} \sim \sigma_{ul} \cdot v \; [=] \; cm^3\, s^{-1}$$

$$\gamma_{ul}(T) = \int \sigma_{ul}(v)\, v\, f_v\, dv$$

Cross-section [cm^2] (computed by quantum methods)

Maxwell distribution of thermal velocities [cm/s]

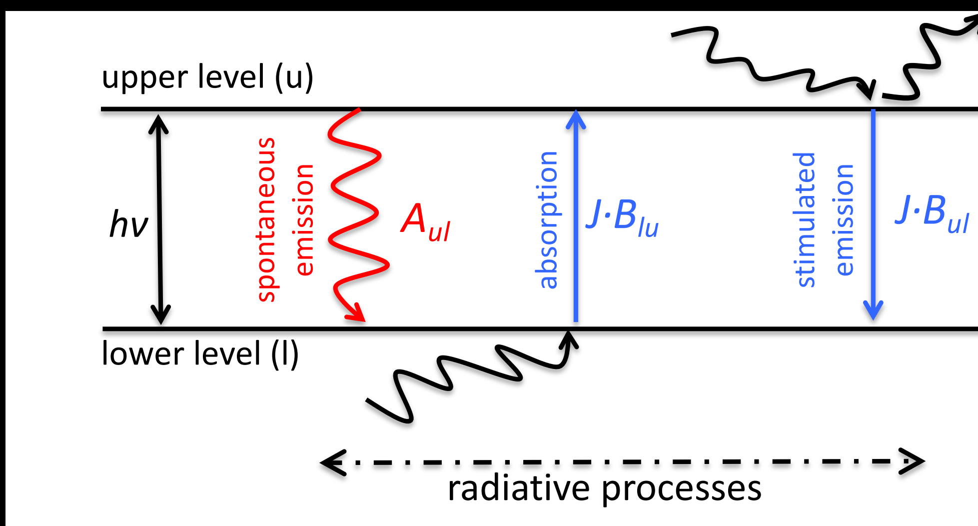


Limiting case: collisional rates << radiative rates

$$\frac{dn_i}{dt} = \sum_{j\neq i} n_j \left(J\cdot B_{ji} + \cancel{\gamma_{ji} n}\right) + \sum_{j>i} n_j A_{ji} - n_i \sum_{j\neq i} \left(J\cdot B_{ij} + \cancel{\gamma_{ij} n}\right) - n_i \sum_{j<i} A_{ij} = 0$$

if $J \sim B_\nu(T_{bg})$ *uniform blackbody radiation field at* T_{bg}

$n_u\, J\cdot B_{ul} + n_u A_{ul} - n_l\, J\cdot B_{lu} = 0$ → $\dfrac{n_u/g_u}{n_l/g_l} = \exp(-h\nu/kT_{bg})$ Boltzmann population distribution at T_{bg}

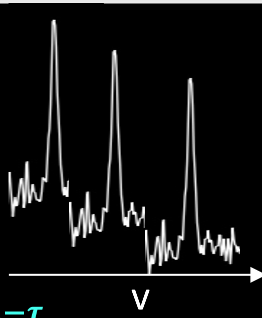


Radiative transfer models

$$\frac{dn_i}{dt} = \sum_{j\neq i} n_j\,(J\cdot B_{ji} + \Upsilon_{ji} n) + \sum_{j>i} n_j A_{ji} - n_i \sum_{j\neq i} (J\cdot B_{ij} + \Upsilon_{ij} n) - n_i \sum_{j<i} A_{ij} = 0$$

Different methods depend on how *J* is computed

NON-LTE BUT LOCAL EXCITATION AND RADIATIVE TRANSFER MODELS:



- **LVG & escape probability:**
  One slab with $J \sim S_{ij}\,(1-\beta)$

  Sobolev 1960 and Castor 1970, *MNRAS*
  RADEX: van der Tak et al. 2007, *A&A*

β = ***The probability that a photon escapes*** $\sim \frac{1-e^{-\tau}}{\tau}$

NON-LOCAL & NON-LTE EXCITATION AND RADIATIVE TRANSFER MODELS:

- **Monte Carlo** (solving Eq. RT):
  (flexible geometries and velocity fields)

  Bernes 1979, *A&A* Hogerheijde & van der Tak 2000, *A&A*
  González-Alfonso & Cernicharo 1993, *A&A*
  Goicoechea et al. 2006, 2022, *A&A*
  Brinch & Hogerheijde 2010 (**LIME**)

- **Accelerated Λ Iteration (ALI):**

  Rybicki & Hummer 1991, *A&A*

- **Coupled escape probability (CEP):**
  (multi slabs)

  Elitzur & Asensio Ramos 2006, *MNRAS*
  Asensio Ramos & Elitzur 2018, *A&A* **MOLPOP-CEP**

Critical density of a transition

$$n_{cr} \sim \frac{A_{ul}}{\gamma_{ul}} \quad [\mathrm{cm}^{-3}]$$

with $\Upsilon_{ul} = \sigma\, v$ [$\mathrm{cm}^3\ \mathrm{s}^{-1}$]

USEFUL LIMITS:

If $n >> n_{cr}$ → collisions dominate excitation → $T_{ex} \approx T_{kin}$ ~ LTE

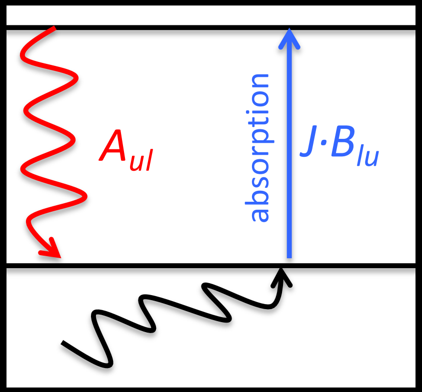
If $n << n_{cr}$ → radiative excitations dominate → $T_{ex} < T_{kin}$

('subthermal' emission)

'Line trapping' as τ increases:

$$n_{cr,eff} \sim \frac{A_{ul} \cdot \beta}{\gamma_{ul}} \sim \frac{A_{ul}}{\gamma_{ul} \cdot \tau} \sim \frac{n_{cr}}{\tau} \rightarrow T_{ex} \uparrow$$

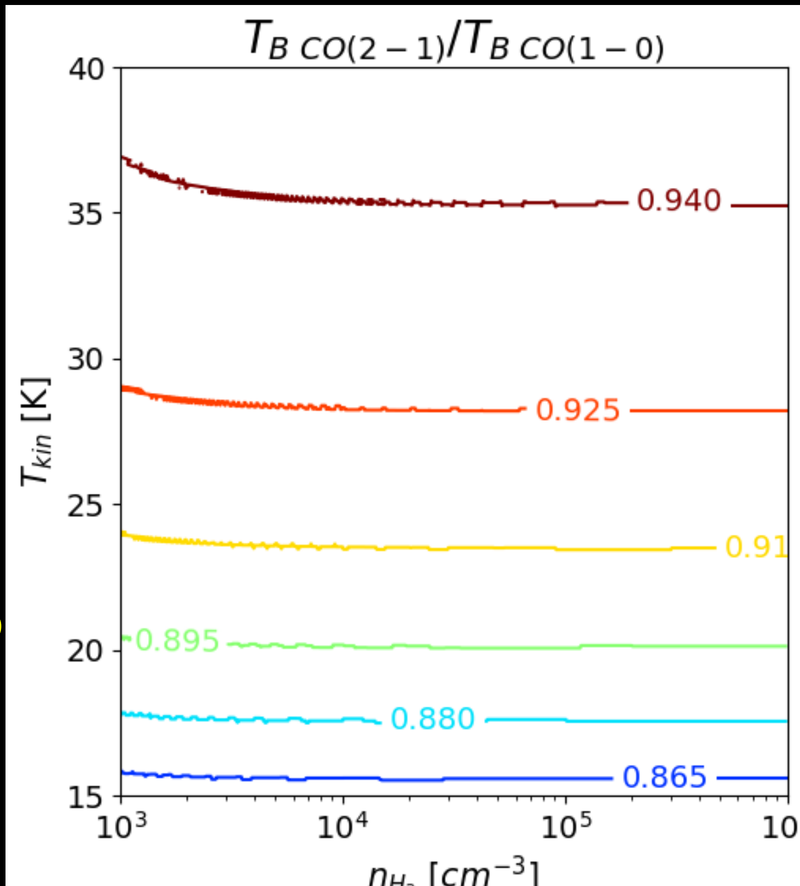
Optically thick lines thermalize at lower densities



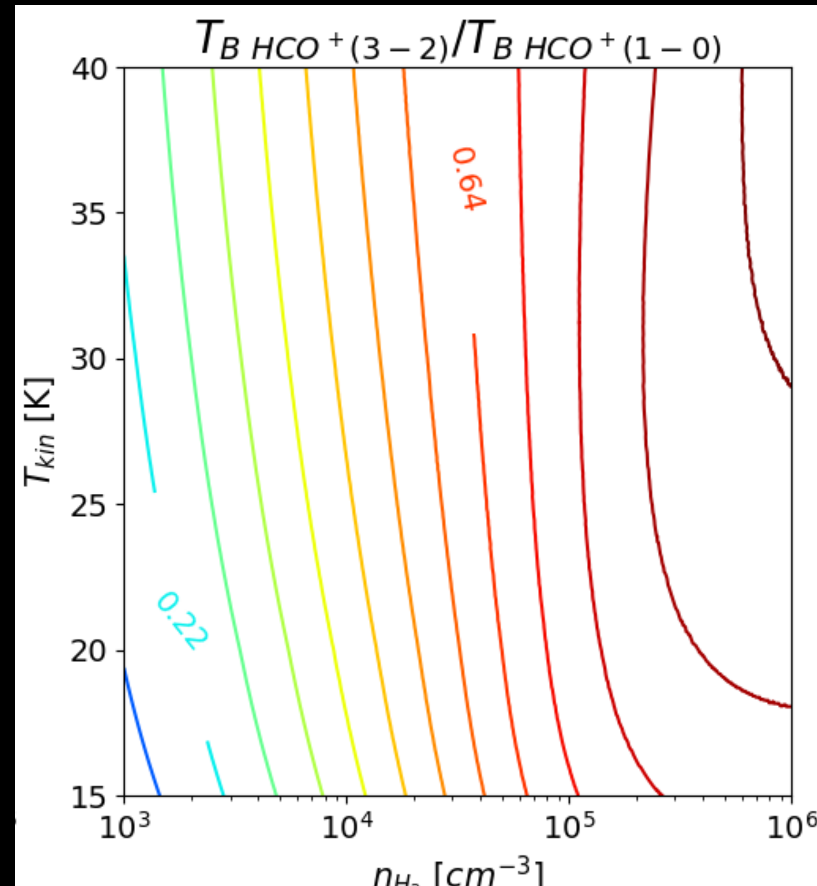
In most cases, one must solve the statistical equilibrium equations with a model …

L. Segal & A. Roueff 2022, using a non-LTE model

CO: low n_{cr}~ 10^{2-3} cm^{-3}



HCO$^+$: high n_{cr}~ 10^5 cm^{-3}



T_{ex} ~ T_{kin}

CO line intensity ratios trace the gas temperature

T_{ex} << T_{kin} (subthermal)

HCO$^+$ line intensity ratios trace the gas density

Spectroscopic & Collisional data

$$\frac{dn_i}{dt} = \sum_{j\neq i} n_j (J\cdot B_{ji} + \gamma_{ji} n) + \sum_{j>i} n_j A_{ji} - n_i \sum_{j\neq i} (J\cdot B_{ij} + \gamma_{ij} n) - n_i \sum_{j<i} A_{ij} = 0$$

The Cologne Database for Molecular Spectroscopy
CDMS

https://cdms.astro.uni-koeln.de/classic/entries/

https://spec.jpl.nasa.gov

LAMDA

Leiden Atomic and Molecular Database

Data format | RADEX

https://home.strw.leidenuniv.nl/~moldata/

Browse collisions | Search collisions | Search articles

Basecol

Ro-Vibrational Collisional Excitation
Database and Utilities

https://basecol.vamdc.eu/index.html

Try to thank the papers with the specific calculations too… !

Radiative transfer models
(extra ingredients…)

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$ → defining τ_ν and S_ν as: $d\tau_\nu = \alpha_\nu\, ds$ $\quad S_\nu = \frac{j_\nu}{\alpha_\nu}$ → $$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

***A)** Gas and dust coexist, affecting the excitation of molecular lines:*

$\alpha_\nu = \alpha_{gas} + \alpha_{dust}$ *with* α_{dust} = *dust absoption coeficient*

e.g., Draine & Lee 84, Ossenkopf & Henning 94

$j_\nu = j_{gas} + j_{dust}$ *with* $j_{dust} = \alpha_{dust} \cdot B(T_{dust})$ = *dust emissivity*

***B) When** chemical formation & destruction processes are comparable to collisional processes:*

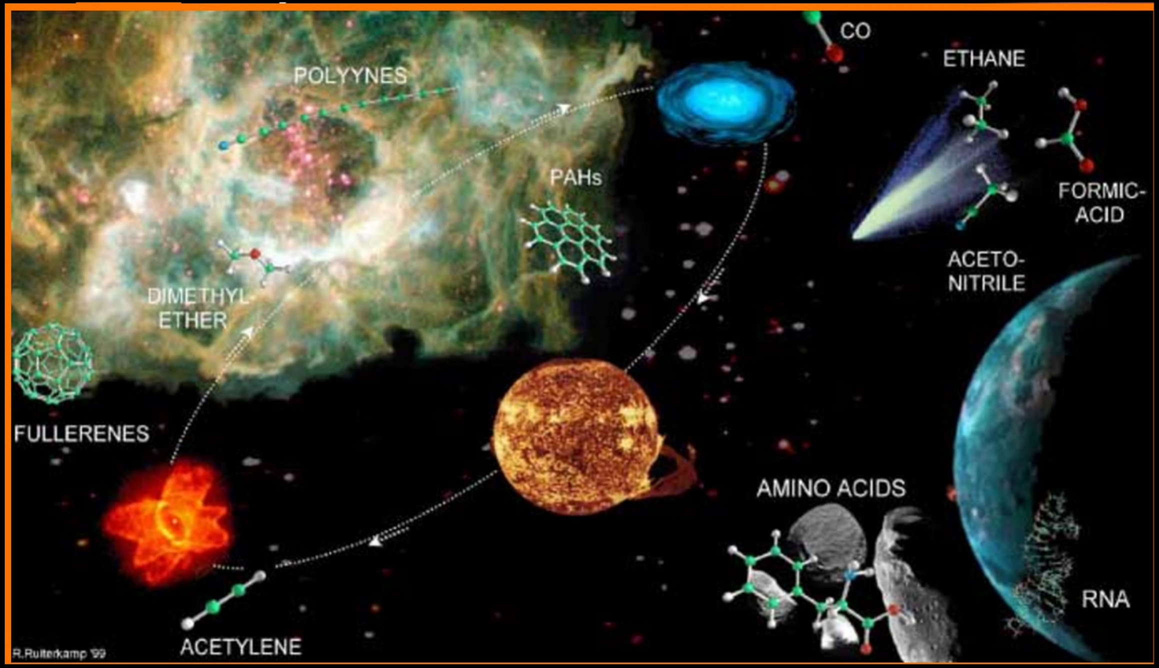
$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = 0 = \mathcal{F}_i - n_i \mathcal{D}_i,$$

J. H. Black 1998

$$\sum_{j>i} n_j A_{ji} + \sum_{j\neq i} n_j \left(B_{ji} \bar{J}_{ji} + C_{ji}\right) + F_i$$
$$= n_i \left(\sum_{j<i} A_{ij} + \sum_{j\neq i} \left(B_{ij} \bar{J}_{ij} + C_{ij}\right) + D_i\right)$$

+Chemical formation and destruction rates

III. Interstellar Chemistry



Where do interstellar molecules come from?
How are they formed?

Molecules in the ISM? Typical Scales…

"Size" of a diatomic molecule, $r \approx 2$ Å $= 2 \cdot 10^{-8}$ cm

Cross-section (surface) $\sigma = \pi r^2 \approx 10^{-15}\ cm^2$

Typical speeds $v \approx 0.1\ km\ s^{-1} = 10^4\ cm\ s^{-1}$

Reactive collision rate $\gamma\ (cm^3\ s^{-1}) = \sigma \cdot v = 10^{-11}\ cm^3\ s^{-1}$

H_2 density in dense clouds $n(H_2) \approx 10^5\ cm^{-3}$

Time between collisions of two molecules **t (s) ≈ 1 / (** $\gamma\ n_{H2}$ **)** ≈ 2 weeks !!

Distance between collisions **d = v t** ≈ 100,000 km !!

SLOW chemistry,

Astrophysicists did not expect many molecules in space…

(SHORT) HISTORY OF INTERSTELLAR CHEMSITRY

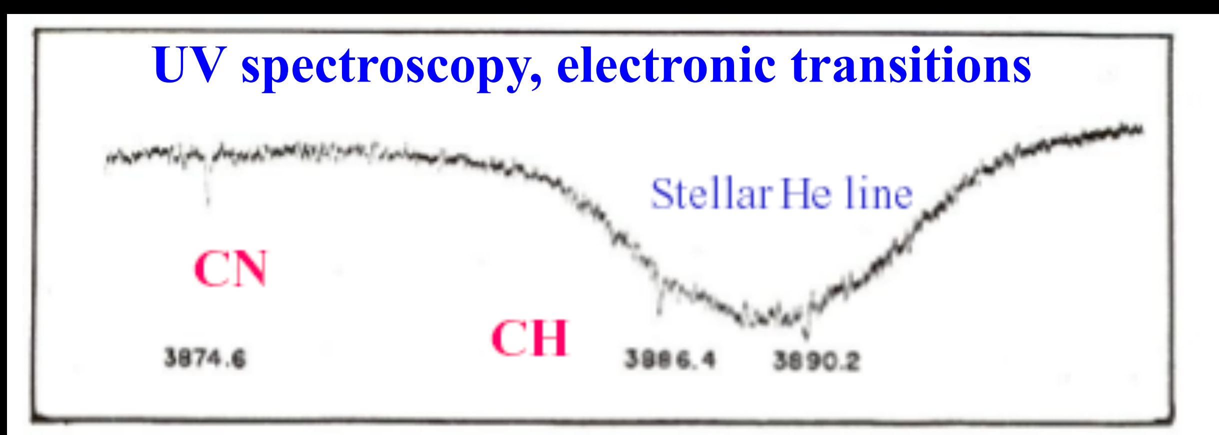
* 1926 – **A. Eddington**

It is difficult to admit the existence of molecules in interstellar space because when once a molecule becomes dissociated there seems no chance of the atoms joining up again.[28]

"Atoms are physics, but molecules are chemistry…"

*** In 1930-1940 <u>three</u> molecules were observed in the line-of-sight toward slightly reddened stars in the near-UV: CN, CH and CH^+**

Swing & Rosenfeld **1937**



MOLECULAR SPECTRA
and
MOLECULAR STRUCTURE

I. SPECTRA OF DIATOMIC MOLECULES

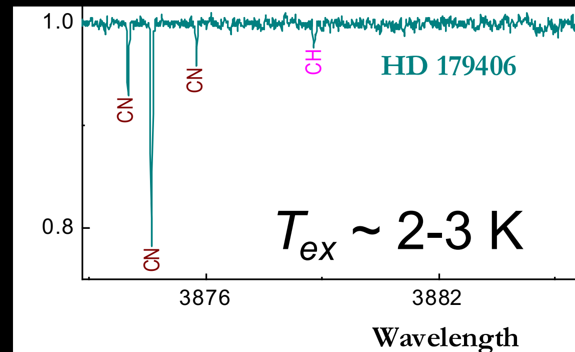
BY

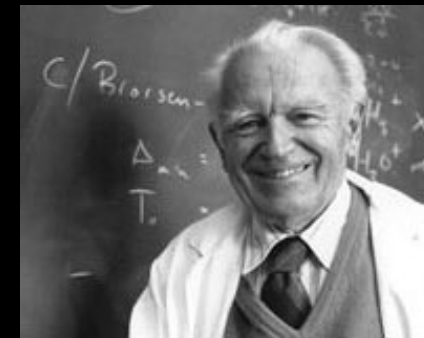
GERHARD HERZBERG, F.R.S.
National Research Council of Canada

With the co-operation, in the first edition, of
J. W. T. SPINKS, F.R.S.C.

SECOND EDITION

CN line absorption toward diffuse ISM clouds





Nobel prize in chemistry in 1971
but he did not know about Cosmology

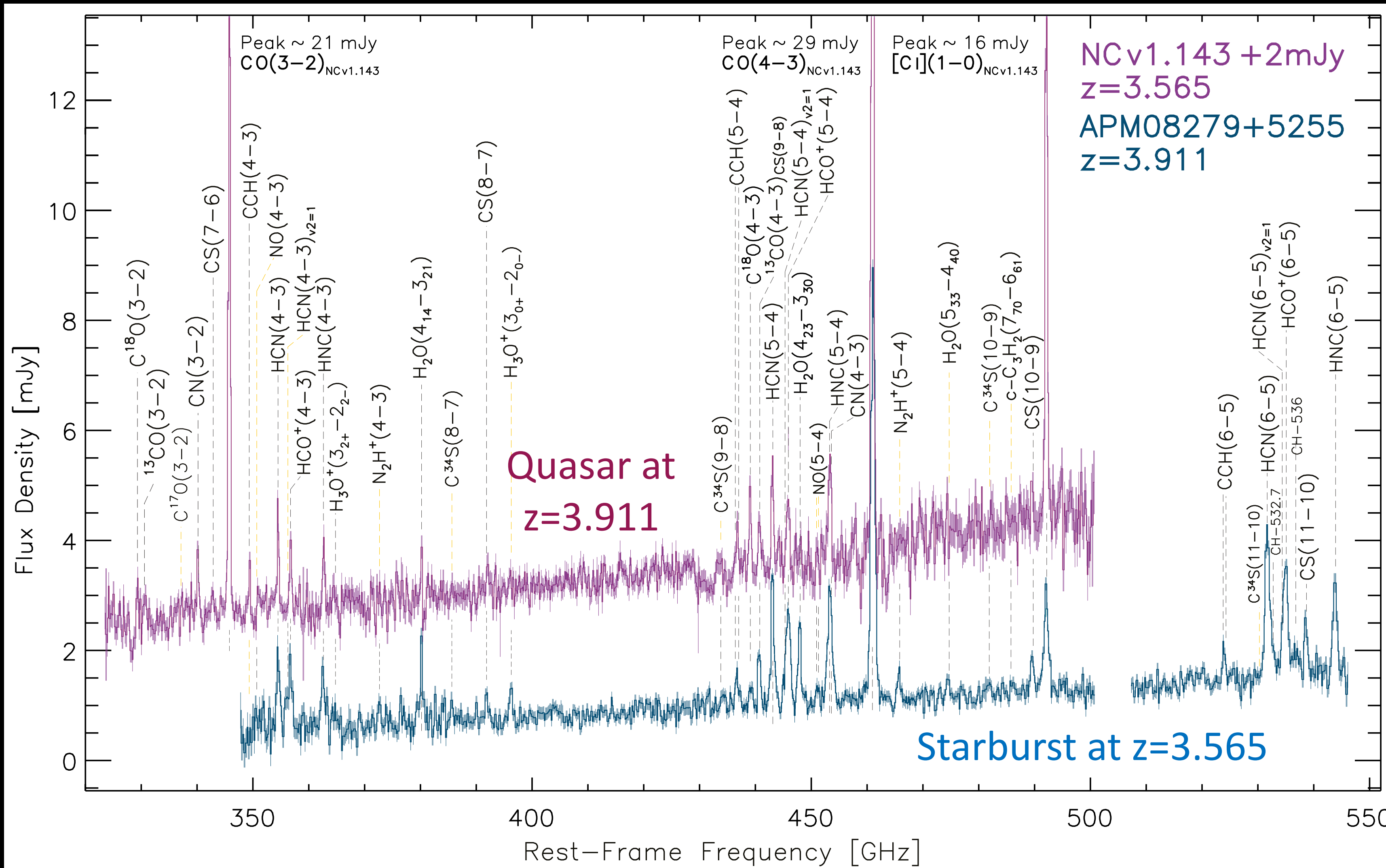
At the low gas densities of diffuse clouds, collisional excitation is negligible, thus T_{ex} (molecules) ≈ $T_{background}$

The observation that in interstellar space only the very lowest rotational levels of CH, CH^+, and CN are populated is readily explained by the depopulation of the higher levels by emission of the far infrared rotation spectrum (see p. 4) and by the lack of excitation to these levels by collisions or radiation. The intensity of the rotation spectrum of CN is much smaller than that of CH or CH^+ on account of the smaller dipole moment as well as the smaller frequency [due to the factor ν^4 in (I, 48)]. That is why lines from the second lowest level ($K = 1$) have been observed for CN. From the intensity ratio of the lines with $K = 0$ and $K = 1$ a rotational temperature of 2.3° K follows, which has of course only a very restricted meaning.

1950

Nearly 15 years before Penzias & Wilson discovery of the CMB in the radio (Nobel Prize) **…**

Yes, molecules are there, everywhere !

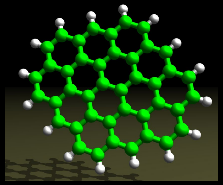


Yang+2023 with IRAM's NOEMA interferometer

$freq_{obs} = freq_{rest\text{-}frame} \cdot (1+z)^{-1}$

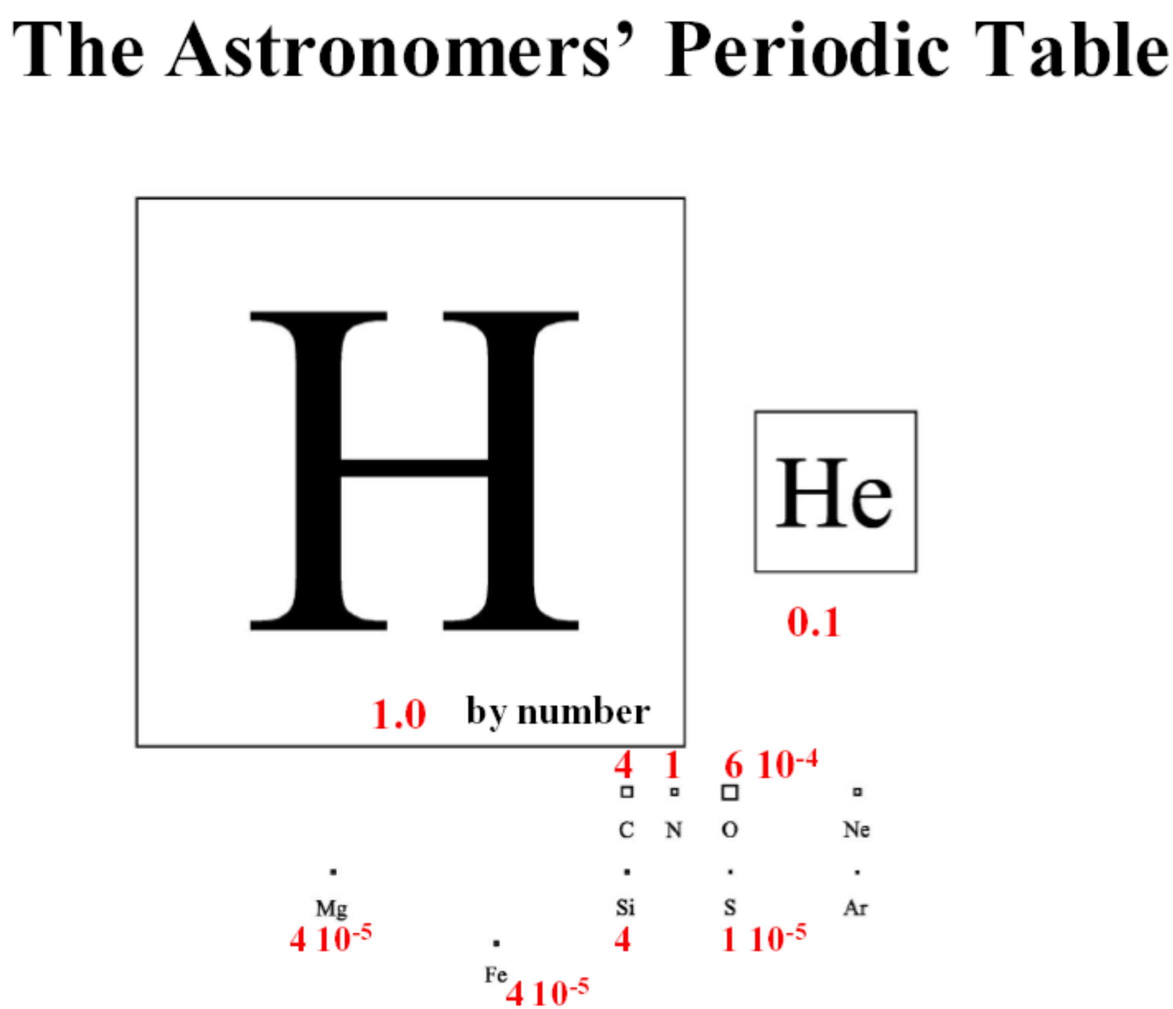
Molecules in Space

- About 330 molecules found in Space (~75 in galaxies)
- H_2 most abundant species (… CO)
- H_2O, CH^+, … simple hydrides → first steps of ISM chemistry
- Polycyclic Aromatic Hydrocarbons



- $HCOCH_2OH$ glycolaldehyde, simplest sugar + COMs …

Elemental abundances in Universe



The number of C, N , O, S ... atoms represents
< 0.1% of H atoms.

B. McCall 2001

I'm sorry Dr. Eddington …
Molecules are very important !

- Exotic chemistry and unique laboratory
- Chemical composition evolves with time

Astrochemistry

- Molecules as diagnostics (T_{kin}, n_{H}, σ_{v}, B, ζ_{CR} , …)
- Gas coolants (gravitational collapse, shocks…)

Astrophysics

Interstellar chemistry is peculiar …

- Diffuse H_2 clouds: n_{H2}~100 cm^{-3}, T_{kin}~100 K
- Dense molecular clouds: n_{H2}~10^5 cm^{-3}, T_{kin}~10-20 K

- Compare with this room: T_{kin}~300 K n ~10^{19} cm^{-3}
- Best laboratory ultra-vacuum chambers: P = $2.5 \cdot 10^{-11}$ mbar → n ~ 10^5 cm^{-3}

ISM = very low densities, very low temperatures → conditions very different compared to Earth !!

+ chemistry affected by presence of UV-photons, X-rays, Cosmic Rays, turbulence, magnetic fields...

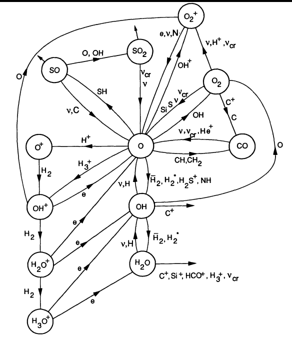
→ ISM chemistry is <u>NEVER</u> in 'thermo-chemical equilibrium'
→ solve two body reaction kinetics: **A + BC = AB + C**
(+ many quantum effects)

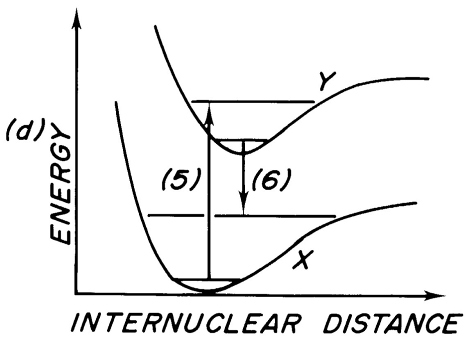
Summarized Interstellar chemistry

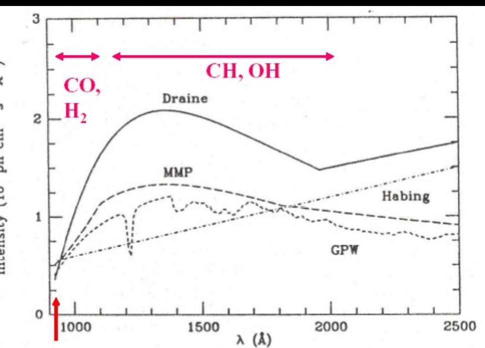
1) **Need to form the basic molecule H_2 → dust grain surfaces**

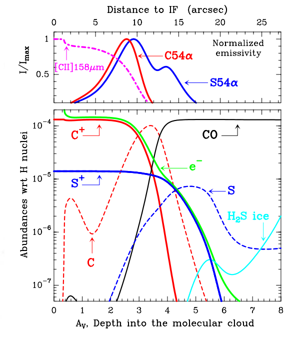
2) **We need atomic** (C^+, S^+, O^+,) and **molecular ions** ($H_2 + O^+ \rightarrow OH^+ + H$):
   - FUV-photons from massive OB-type stars
   - Cosmic-ray particles

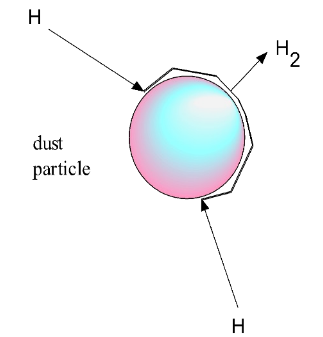
Gas-phase molecules are (predominantly) synthesised in exothermic reactions in the gas and on the surfaces of tiny grains (many exceptions!).











BIMOLECULAR REACTIONS IN THE ISM

$$A + BC \xrightarrow{k} AB + C$$

$$AB + h\nu \xrightarrow{\beta} \ldots$$

$k\,(T)$ = ***"reaction rate coefficient"***

$[k] = cm^{+3}\, s^{-1} \sim \sigma\,(cm^2) \cdot v\,(cm\, s^{-1})$

β = "***photodissociation rate***"

$[\beta]$ = (molecules) s^{-1}

F = Formation rate of AB $= k \cdot \mathbf{n(A)} \cdot \mathbf{n(BC)}$ $[cm^{-3}\, s^{-1}]$

D= Destruction rate of AB $= \beta \cdot \mathbf{n(AB)}$ $[cm^{-3}\, s^{-1}]$

n(AB) as function of time ?

$d/dt\;\; n(AB, t) = F - D = k\, n(A, t)\, n(BC, t) - \beta\, n(AB, t)$

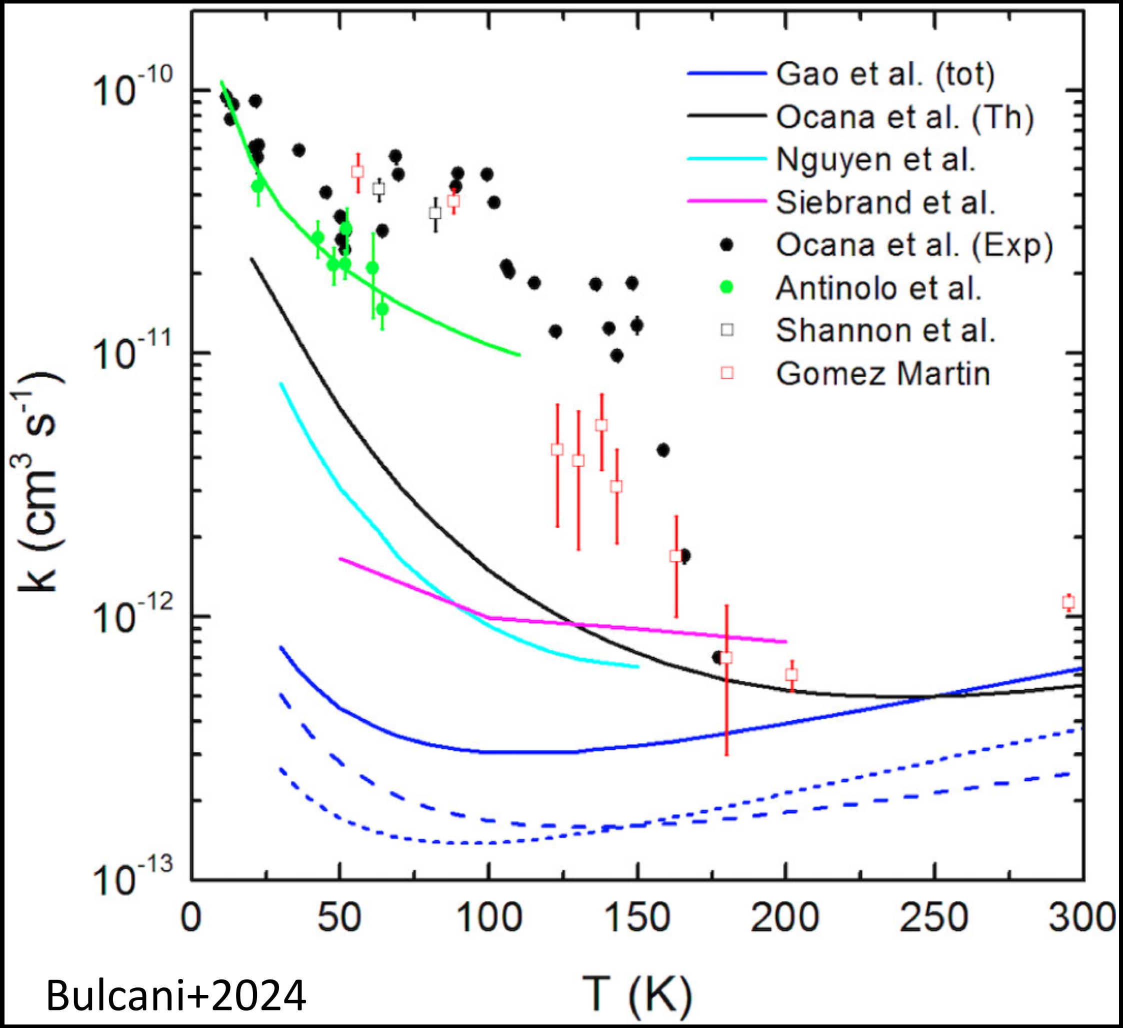
Steady-state → *d/dt n(AB) = 0* → $\boxed{\mathbf{n(AB)} = k\, n(A) \cdot n(BC) / \beta}$

(time to reach steady-state is ~1/β, β~10^{-10} s^{-1} 1/β~300 yr)

Astrochemical models contain thousands of reactions but only a few reaction types:

- Formation of bonds **reaction rate k(T) ~ $\sigma \cdot v$:**
  - Radiative association: 10^{-13} cm^{3}s^{-1} $X^+ + Y \rightarrow XY^+ + h\nu$
  - Associative detachment $X^- + Y \rightarrow XY + e$
  - Grain surface: $3 \cdot 10^{-17}$ cm^{3}s^{-1} (*e.g.* H_2) $X + Y{:}g \rightarrow XY + g$
- Destruction of bonds
  - Photo-dissociation: 10^{-9}–10^{-12} s^{-1} $XY + h\nu \rightarrow X + Y$
  - Dissociative recombination: 10^{-6} cm^{3}s^{-1} $XY^+ + e \rightarrow X + Y$
  - Collisional dissociation: $XY + M \rightarrow X + Y + M$
- Rearrangement of bonds
  - Ion-molecule reactions: 10^{-9} cm^{3}s^{-1} $X^+ + YZ \rightarrow XY^+ + Z$
  - Charge-transfer reactions: 10^{-9} cm^{3}s^{-1} $X^+ + YZ \rightarrow X + YZ^+$
  - Neutral-neutral reactions: 10^{-12} cm^{3}s^{-1} + $E_{barrier}$ $X + YZ \rightarrow XY + Z$

Negative temperature dependence of many reactions



$OH + CH_3OH \rightarrow CH_3O + H_2O$

$k(T)=a(T/300)^b \exp(-c/kT)$
$[cm^3\ s^{-1}]$

Arrhenius-law fit

FAST COLD INTERSTELLAR CHEMISTRY !

PHOTO-DISSOCIATION of MOLECULAR GAS:

- **Stellar FUV photons** dissociate molecules:

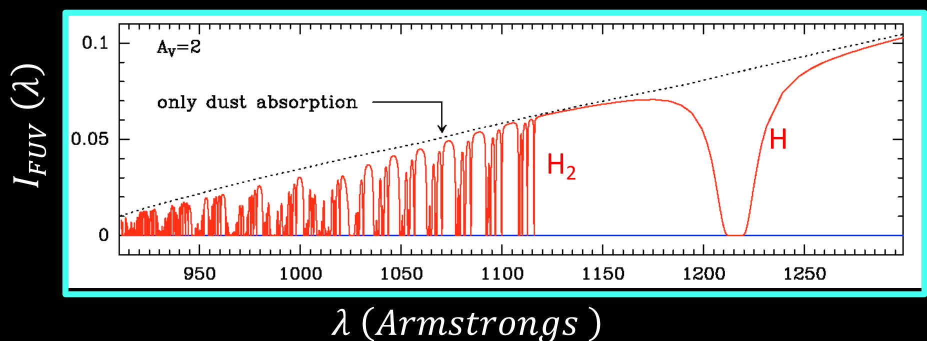
$$CO + h\nu \rightarrow C + O \qquad \beta_{CO} = G_0 \cdot 2.4\cdot 10^{-10}\ (s^{-1})$$

Photodissociation rate β: $\beta\,(\textbf{dissociation}\ s^{-1}) = \int_{911A}^{2400A} I_{FUV}(\lambda)\,\sigma_{dissociation}(\lambda)\,d\lambda$

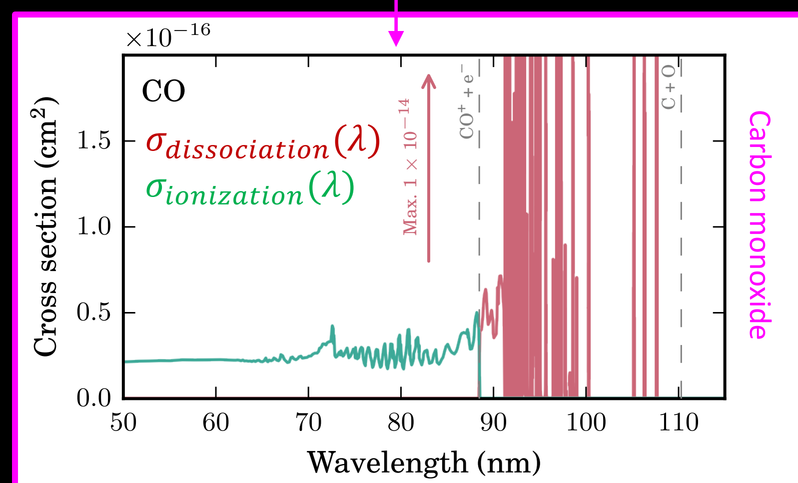
Stellar physics & FUV propagation

Molecular Physics

FUV radiation field inside a molecular cloud



Goicoechea & Le Bourlot 2007



Heays, Bosman, van Dishoeck 2017

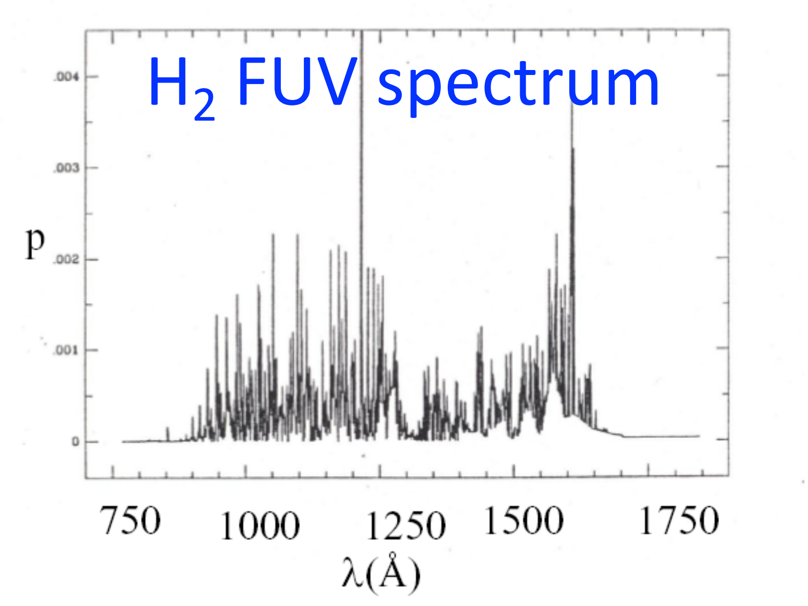
$I_{FUV}(\lambda)$ = **FUV radiation field** in **photons cm^{-2} s^{-1}** at each λ and each cloud-depth position

$\sigma_{dissociation}(\lambda)$ = photodissociation cross-section in **cm^2** → **experiments** or **quantum calculations**

Dark molecular clouds are not completely dark

Molecular clouds with $n(H_2) > 10^3$ cm^{-3}

Cosmic-ray induced FUV radiation ("secondary FUV photons")

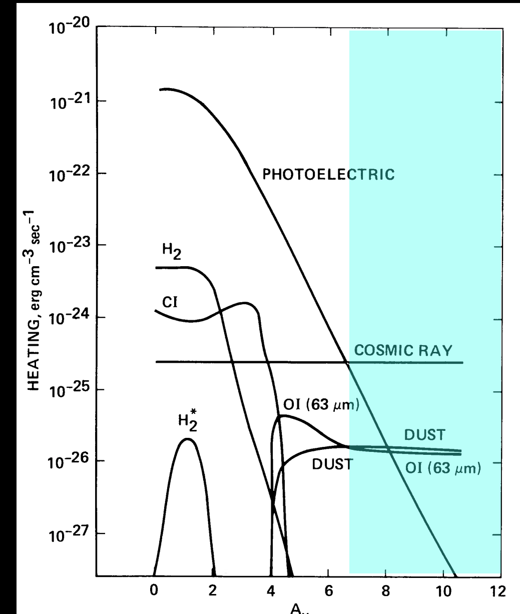


$H_2 + CR \Rightarrow H_2^+ + e^*$

$H_2 + e^* \Rightarrow H_2^* + e$

$H_2^* \Rightarrow H_2 + h\nu_{FUV}$

Prasad & Tarafdar 1983
Gredel et al. 1987



$G_0 = 10^{-4}$ deep inside molecular clouds

(May affect the chemistry of grain ice mantles in cloud interiors)

(Astro)chemical reaction data bases

Gas-phase chemical reactions:

Typical models contain ~5000 reactions between ~450 species up to 13 atoms

https://umistdatabase.uk (**UMIST**-UDFA, T. Millar et al.)

http://kida.obs.u-bordeaux1.fr (**KIDA**-Bordeaux, Wakelam, Herbst, et al.)

http://home.strw.leidenuniv.nl/~ewine/photo/ (**Photo-rates,** E. van Dischoeck)

$k(\mathrm{T})=a(\mathrm{T}/300)^{b}\,\exp\,(-c/k\mathrm{T})$ [$\mathrm{cm}^3\,\mathrm{s}^{-1}$] ***Arrhenius law***

$k_{photo}(A_v)=G_0\cdot\beta\,\exp\,(-\,\alpha\,A_v)$ [s^{-1}]

Computational chemistry

$$A + B \xrightarrow[k_{AB}]{} X + Y$$

$$X + C \xrightarrow[k_{XC}]{} D + E$$

$$X + h\nu \xrightarrow[\beta_X]{} \text{products}$$

(on grains: $A_{ice} + B_{ice} \rightarrow X_{ice} + Y_{ice}$; $X_{ice} + h\nu\, /\, T \rightarrow X_{gas}$)

One differential equation per species in the network:

$$d/dt\ \ n_X = F - D = \Sigma_A \Sigma_B\, k_{AB}\, n_A\, n_B - (\Sigma_C\, k_{XC}\, n_C + \beta_X)\, n_X$$

+ Conservation equations:

Carbon $n_C = n(C^+) + n(C) + n(CO) + n(CH) \ldots + 2n(C_2) + 2n(C_2H) + \ldots$

…

Charge $n_e = n(C^+) + n(H^+) + n(H_3^+) + \ldots$

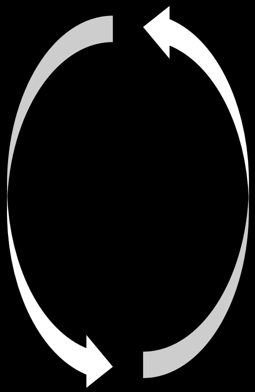
SOLVED ITERATIVELY

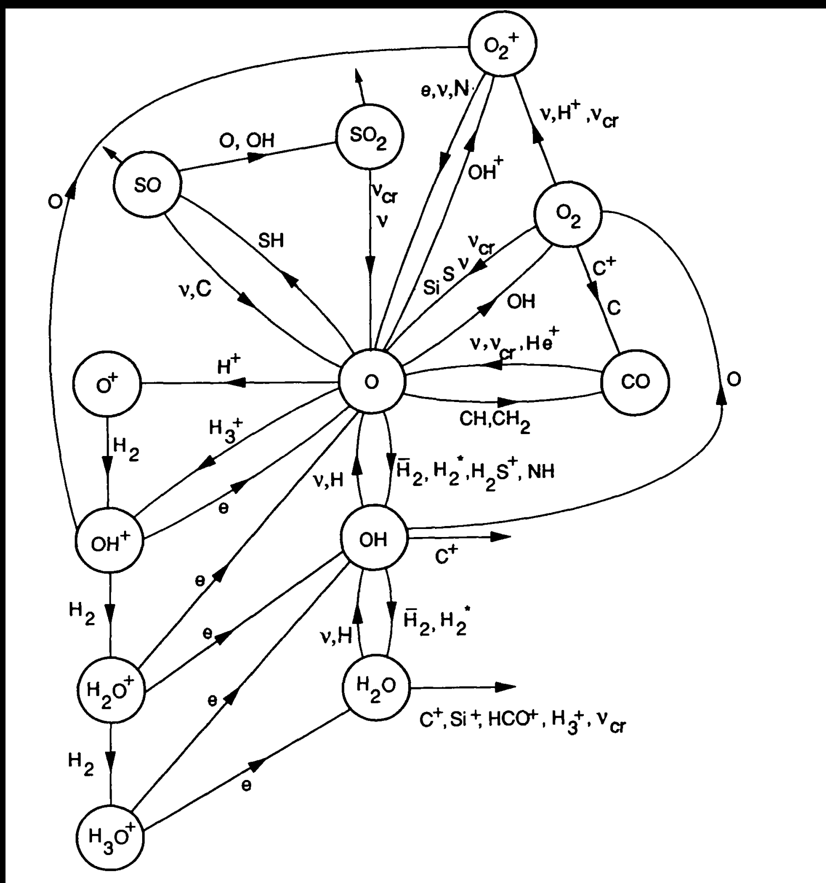
(*eg.* Netwon-Raphson techniques

when dn/dt = 0 steady-state)

Ideal astrochemical models

- ***Input*** radiation field (UV) → ***output*** atomic/molecular line emission
- Gas heating & cooling → T_{gas} (depends on composition!) + T_{dust}
- Chemistry (gas + grain surface) → abundances (depend on T)





Several iterations needed

But remember, reaction rates are often uncertain…,

→ **Model predictions are uncertain (factors ~2 to 10)**

e.g. Wakelam et al. 2005

The *Meudon* PDR code (public)

ISMServices

CODES ISMDB TOOLS TECHNOLOGIES PARTNERS REGIST

PDR Code | Download | Tools

https://pdr.obspm.fr

PDR Code

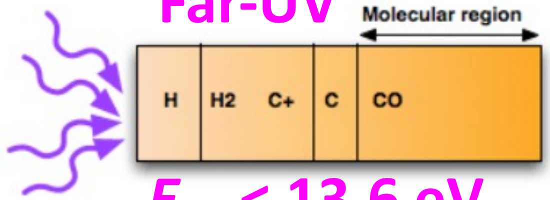
FUV-dominated Photodissociation regions

The code considers a stationary plane-parallel slab of gas and dust illuminated by a radiation field coming from one or both sides of the cloud. The incident radiation field can be the Interstellar Standard Radiation Field (ISRF) and/or a star.

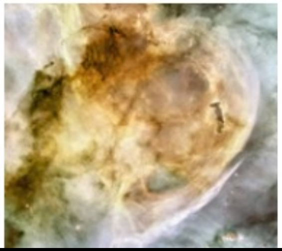
It solves at each point in the cloud, the radiative transfer in the UV taking into account the absorption in the continuum by dust and in discrete transitions of H and H2. The model computes the thermal balance taking into account heating processes such as the photoelectric effect on dust, chemistry, cosmic rays, etc. and cooling resulting from infrared and millimeter emission of the abundant species.

Chemistry is solved for any number of species and reactions.

Far-UV



E_{ph} < 13.6 eV



Once abundances of atoms and molecules and level excitation of the most important species have been computed at each position in the cloud, line intensities and column densities can be deduced by a post-processor code.

The Meudon PDR code can be used to study the physics and chemistry of diffuse clouds, photodissociation regions (PDRs), dark clouds, ...

LERMA – Paris Observatory

Scientists and engineers

Emeric Bron *(scientist)*
David Languignon *(engineer)*
Jacques Le Bourlot *(scientist)*
Franck Le Petit *(scientist)*
Nicolas Moreau *(engineer)*
Evelyne Roueff *(scientist)*

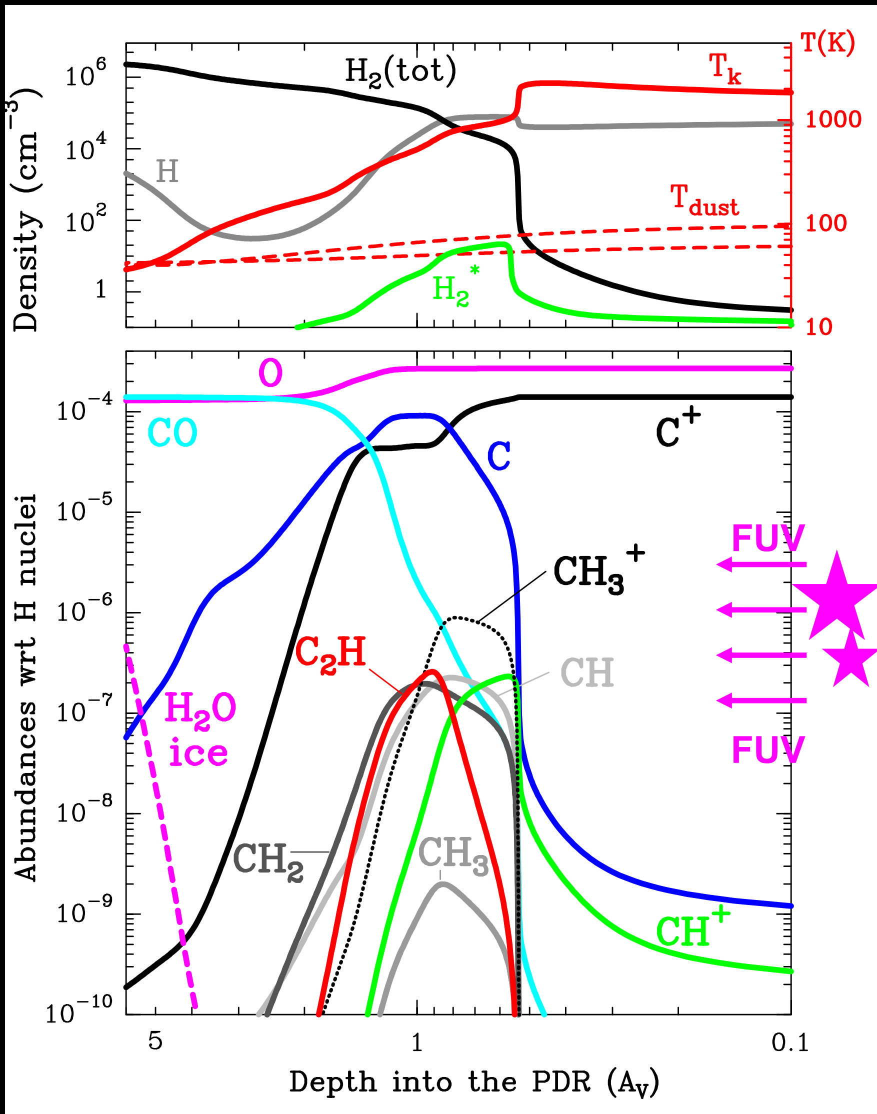
References

- Le Petit et al., 2006, ApJS, 164, 506
- Goicoechea et al., 2007, A&A, 467, 1
- Gonzalez Garcia et al., 2008, A&A, 485, 127
- Le Bourlot et al., 2012, A&A, 541, 76
- Bron E., 2014, Thesis
- Bron et al., 2014, A&A, 569, 100
- Bron et al., 2016, A&A, 588, 27

G_0
P_{th}
γ_{CRs}
M^+
...

FUV radiative transfer + heating/cooling + chemistry + molecular excitation

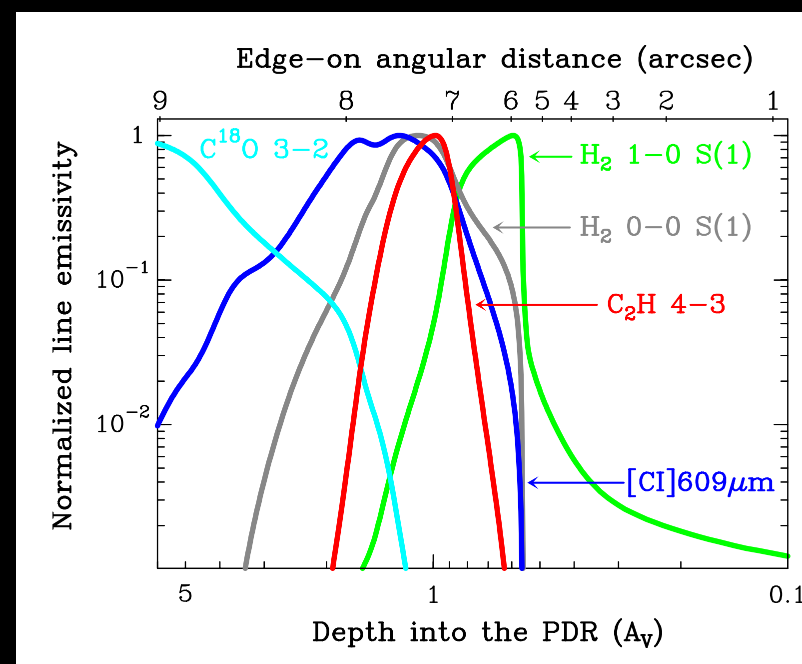
Typical output



Physical structure

Chemical abundances

Line emission stratification:



Example from Goicoechea +2025, A&A

The Orion Bar PDR, $G_0=2\cdot10^4$, P_{th} = 10^8 K cm^{-3}

https://ism.obspm.fr/ismdb.html

The InterStellar Medium DataBase (**ISMDB**) allows quick and easy access to precalculated theoretical models for various ISM conditions and objects. ISMDB includes models produced by the Meudon PDR code and the Paris-Durham shock code.

Presently, ISMDB gives access to several thousands PDR 1.5.4 models covering different astrophysical conditions. Later, it will also contains shock models produced by the Paris-Durham shock code and it will be extended to other astrophysical conditions.

Prepare and interpret observations

To prepare and interpret observations, ISMDB provides an inverse search service to allow:

- queries on observables to find the best models that match observations
- access to line intensity maps in a parameter space (ex: density, UV flux) to prepare observations
- download model results without running the code

Search models in ISMDB

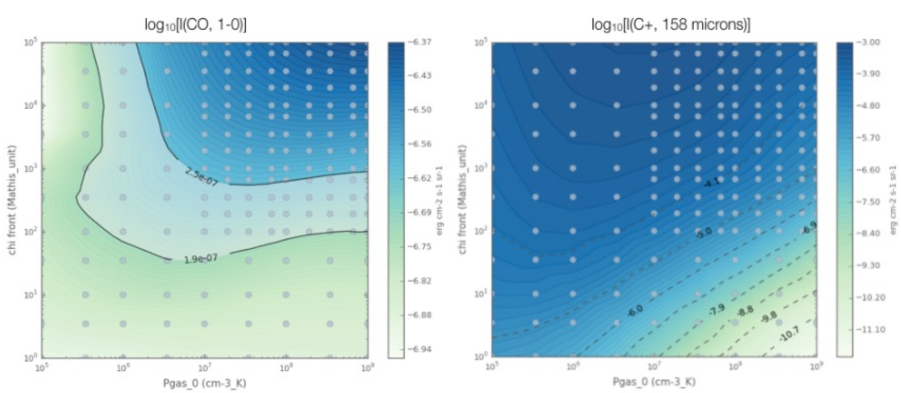
Examples

To find the best models that have I(CO 1-0) between 2.4E-9 and 7.2E-8 erg cm-2 s-1 sr-1 for a face on PDR, enter in ISMDB:

- I(CO v=0,J=1->v=0,J=0 angle 00 deg) > 1.9e-7
- I(CO v=0,J=1->v=0,J=0 angle 00 deg) < 2.5e-7

To get estimations of the C+ 158 microns line intensity, enter in ISMDB:

- I(C+ El=2P,J=3/2->El=2P,J=1/2 angle 00 deg)



Content of ISMDB

October 2021

- PDR 1.5.4 – **isochoric PDR models**
- PDR 1.5.4 – **isobaric PDR models**

December 2016

- PDR 1.5.2 – **isochoric PDR models**
- PDR 1.5.2 – **isobaric PDR models**

Pre-run PDR models & quick diagnostic plots

Shock models coming soon…

The PDR toolbox

PhotoDissociation Region Toolbox

TOOLS MODELS DOCUMENTS ABOUT CONTACT

https://dustem.astro.umd.edu/tools.html

M. Wolfire & M. Pound

Ultraviolet photons from O and B stars strongly influence the structure and emission spectra of the interstellar medium. The UV ionize hydrogen $h\nu > 13.6\mathrm{eV}$ will create the H II region around the star, but lower energy UV photons escape. These far-UV ph $6\ \mathrm{eV} < h\nu < 13.6\ \mathrm{eV}$) are still energetic enough to photodissociate molecules and to ionize low ionization-potential atoms suc sulfur. They thus create a ***photodissociation region*** (PDR) just outside the H II region. In aggregate, these PDRs dominates the heat interstellar medium. The gas is heated by photo-electrons from grains and cools mostly through far-infrared fine structure lines l

The **PDR Toolbox** is an open-source, science-enabling tool for the community, designed to help astronomers determine the physi photodissociation regions from observations. Typical observations of both Galactic and extragalactic PDRs come from ground- a submillimeter, and far-infrared telescopes such as ALMA, SOFIA, JWST, Spitzer, and Herschel. Given a set of observations of spe intensities, PDR Toolbox can compute best-fit FUV incident intensity and cloud density based on our models of PDR emission. O emission excitation diagrams to determine temperature, column density, and ortho-to-para ratio.

The current version is 2.4.4 (released Feb 07, 2025)

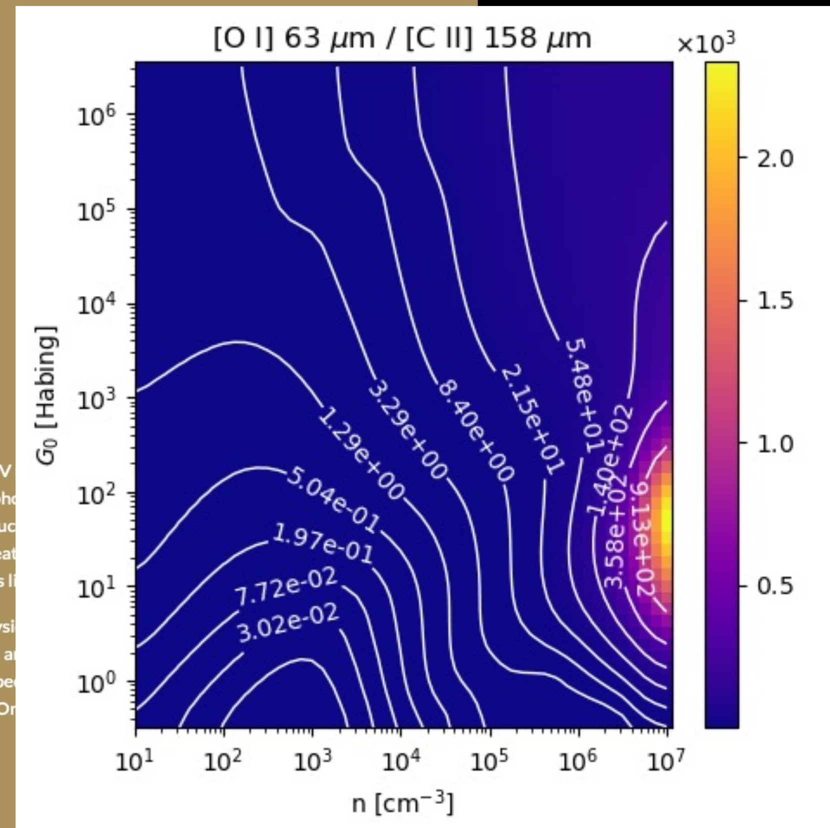
Release Highlights

- **[O I] 1.316 μm Diagnostic Diagram**

  We provide guidance to help to take into account viewing inclination angle when interpreting measured [O I] 1.316 μm emission line (e.g., with JWST).

- **LMC metallicity surface temperature**

  We have computed models for surface temperature at the metallicity of the Large Magellenic Cloud (z=0.5).



Quick diagnostic plots

Cloudy photoionization code (public)

README.md

https://gitlab.nublado.org/cloudy/cloudy

HII regions and more

Cloudy

Cloudy is an *ab initio* spectral synthesis code designed to model a wide range of interstellar "clouds", from H II regions and planetary nebulae, to Active Galactic Nuclei, and the hot intracluster medium that permeates galaxy clusters.

Cloudy has been in continuous development since 1978, led by Gary Ferland, and in close collaboration with a number of scientists -- see the list of contributors.

Version

Includes extreme-UV (EUV) with E_{ph} > 13.6 eV

The current version of Cloudy is C23, released in 2023. A summary of what is new is available here.

If you used Cloudy in your research, please cite our most recent release paper

Q_{Ly}

U

n_e

T_e

EUV + FUV + heating/cooling + HII region ionization + chemistry

There are other models of PDRs, shocks, HII regions …

Interstellar chemistry makes this…

Diffuse clouds

Low densities, warm gas ~100 K
FUV heating & CR ionization

Simple reactive molecules:
OH^+, CH^+ , CH, …

Cold & dense clouds

High densities, cold gas, depletion, CR ionization…

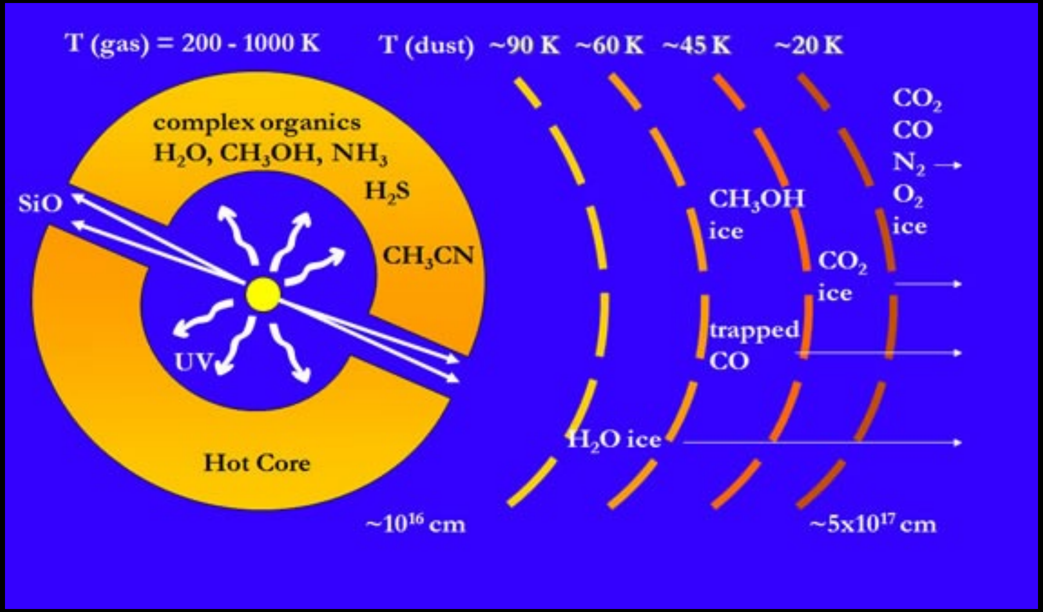
H_2O and even CO freeze out
Deuterated species: N_2D^+ …

Outflows and shocks

High-Temperature chemistry
Grain sputtering

High-*J* CO, H_2O, OH, SiO …

Hot Cores around massive protostars



Ice-mantle evaporation
Warm-temperature chemistry

CH_3OH, and saturated COMs

Photodissociation regions

Photochemistry,
UV dissociation and gas heating

IR emission from PAHs & H_2
Reactive molecular ions …

Circumstellar envelopes around evolved stars

High densities, dust formation

with metals: NaCl…
refractory: TiO, SiC_2…

Take home messages

- ISM = A very important component of galaxies …
- The ISM is slowly converted into stars. As the die, they return enriched matter back.
- UV , cosmic rays and shocks heat the ISM → Stellar and ISM evolution are tightly coupled
- Fascinating physical and chemical (micro) processes → collaborate with quantum chemists and experimentalists
- New developments: magnetic fields and turbulence → more sophisticated MHD simulations
- Bright future: ALMA, NOEMA, IRAM30m, JWST, SKA, … be a multiwavelength astronomer !