

Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11	<i>Today: Introduction & Overview</i>	<i>(Beuther)</i>
10.11	Physical processes I	(Beuther)
17.11	Physical processes II	(Beuther)
24.11	Molecular clouds as birth places of stars	(Suri)
01.12	Molecular clouds (cont.), Jeans Analysis	(Suri)
08.12	Collapse models I	(Henning)
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----- Christmas break -----		
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02.02	Accretion disks II	(Henning)
09.02	High-mass star formation, clusters and the IMF	(Suri)
16.02	Extragalactic star formation	(Henning)
23.02	Examination week, no star formation lecture	

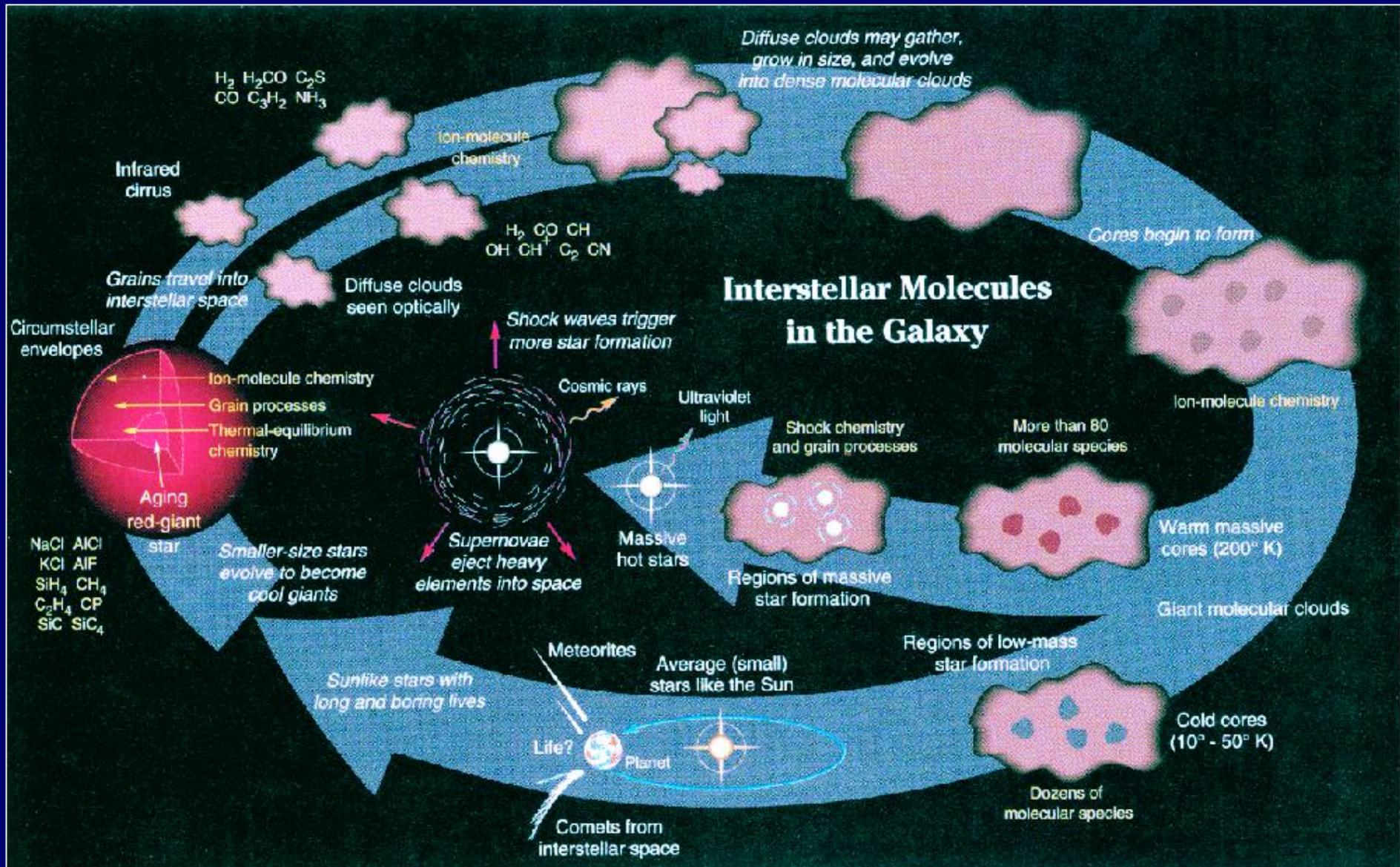
Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html
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Topics today

- The ISM, molecules and depletion
- Heating and cooling
- Radiation transfer and column density determination

The cosmic cycle

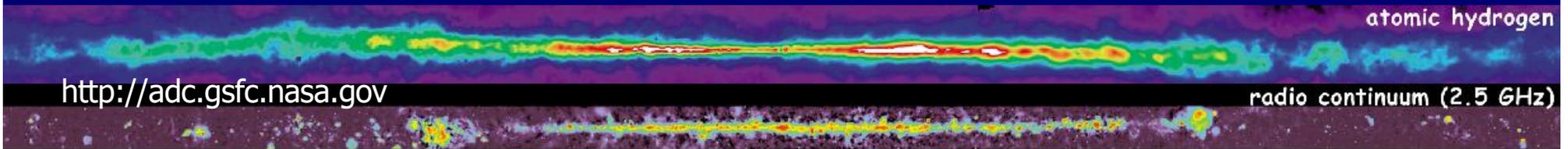


Properties of Molecular Clouds

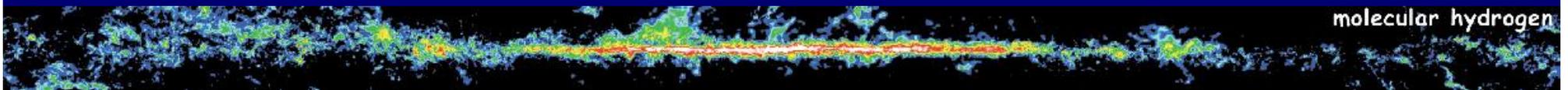
Type	n [cm ⁻³]	Size [pc]	T [K]	Mass [M _{sun}]
Giant Molecular Cloud	10 ²	50	15	10 ⁵
Dark Cloud Complex	5x10 ²	10	10	10 ⁴
Individual Dark Cloud	10 ³	2	10	30
Dense low-mass cores	10 ⁴	0.1	10	10
Dense high-mass cores	>10 ⁵	0.1-1	10-30	100-10000

Basics

Neutral and ionized medium



Stars form in the dense molecular gas and dust cores



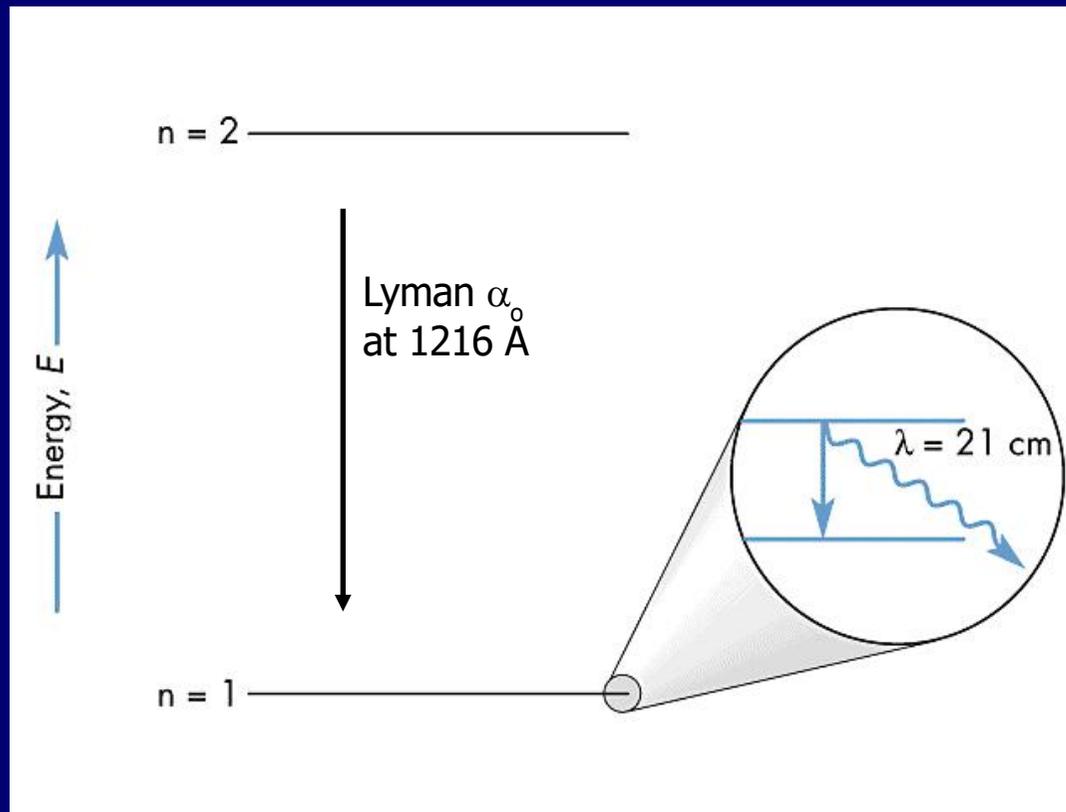
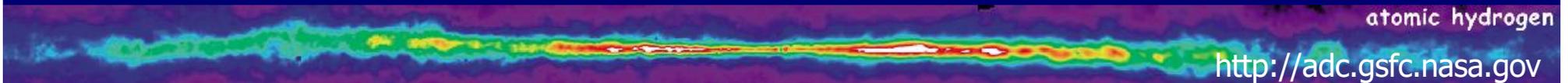
Most important astrophysical tools:

Spectral lines emitted by various molecules

Absorption and thermal emission from dust

The Interstellar Medium I

Atomic Hydrogen



The 21cm line arises when the electron spin S flips from parallel ($F=1$) to antiparallel ($F=0$) compared to the Proton spin I .

$$\Delta E = 5.9 \times 10^{-5} \text{ eV}$$

The Interstellar Medium I

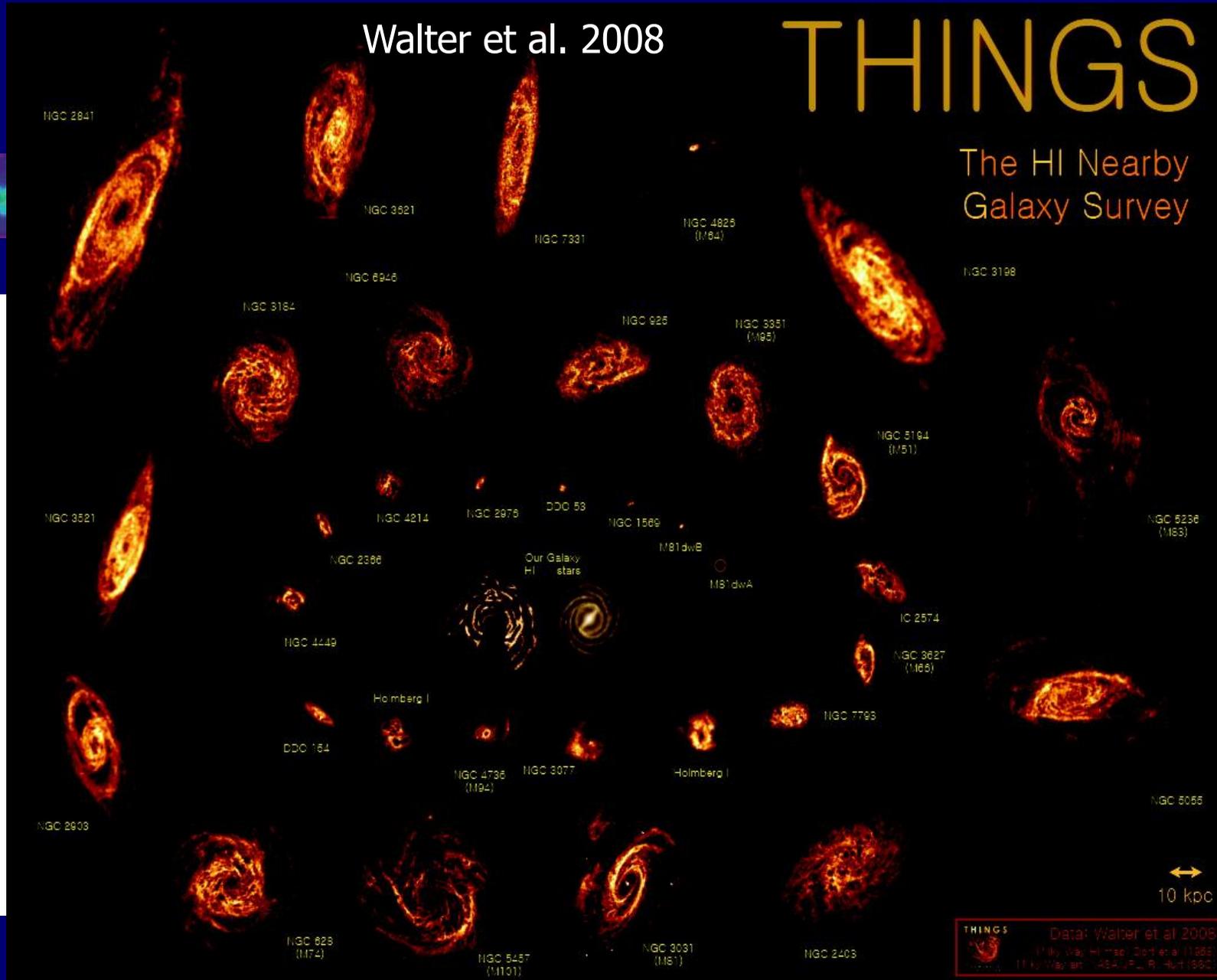
Walter et al. 2008

THINGS

The HI Nearby
Galaxy Survey

atomic hydrogen
sfc.nasa.gov

Energy, E ↑



en the
parallel
)
spin I.

The Ionized gas

Ionized gas

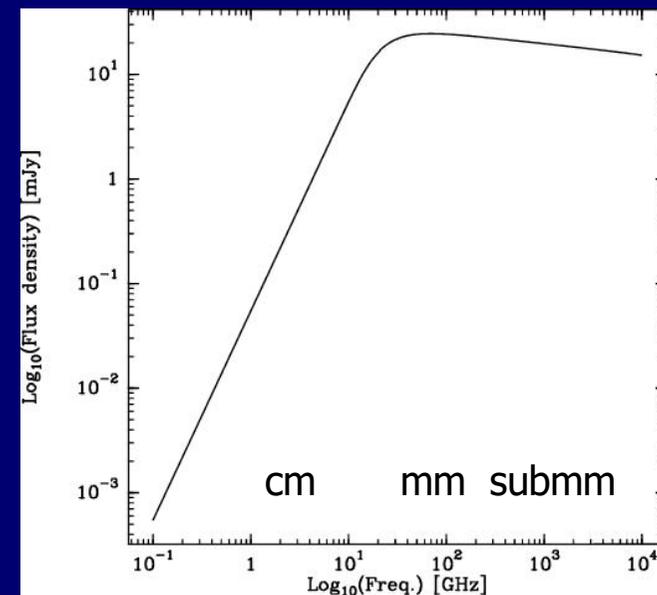
<http://adc.gsfc.nasa.gov>

radio continuum (2.5 GHz)

- Hydrogen recombination lines from optical to cm wavelengths
- Emission lines from heavier elements --> derive atomic abundances

He/H	0.1
C/H	3.4×10^{-4}
N/H	6.8×10^{-5}
O/H	3.8×10^{-4}
Si/H	3.0×10^{-6}

- Free-free emission between e^- and H^+



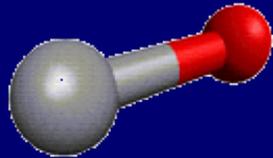
The Molecular ISM

Molecular Hydrogen

<http://adc.gsfc.nasa.gov>

molecular hydrogen

Carbon monoxide CO

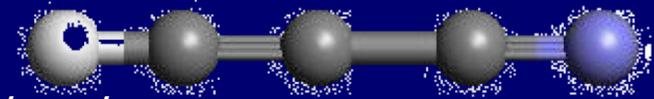


Formaldehyde H₂CO



<http://www.cdms.de>

Cyanoacetylene HC₃N



Excitation mechanisms:

- Rotation --> usually cm and (sub)mm wavelengths
- Vibration --> usually submm to FIR wavelengths
- Electronic transitions --> usually MIR to optical wavelengths

Molecular ISM Basics

History:

- Late 1930s: Detection of CH, CH⁺ and CN in diffuse clouds by absorption of optical light from background stars
- 1960s: Detection of OH, NH₃ and H₂O at radio wavelength
- 1970: CO

Formation of molecules is an energy problem:

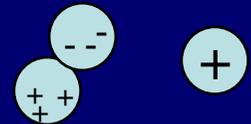
Two atoms approach each other with positive total energy
→ rebound if no energy can be given away

Possibilities:

- Simultaneous collision with 3rd atom carrying away energy
--> unlikely at the given low densities
- Form a molecule in excited state, and then radiating away energy
--> probability of such radiative association low as well

Molecular ISM Basics

- Ion-molecule or ion-atom reactions can solve energy problem
- Neutral-neutral reactions on dust grain surfaces (catalytic) important
- Ion induces dipole moment in atom or molecule
 - > creates electrostatic attraction between the two.
 - > effective cross section increases over geometric values
- At low temperatures such reactions account for large fraction of molecules.
- However, not enough ions to account for large H_2 abundances
 - > grain surface chemistry important
- Simple molecules like CO or CS → ion-molecule chemistry,
- More complex molecules → grain surface chemistry important



Molecular ISM Basics

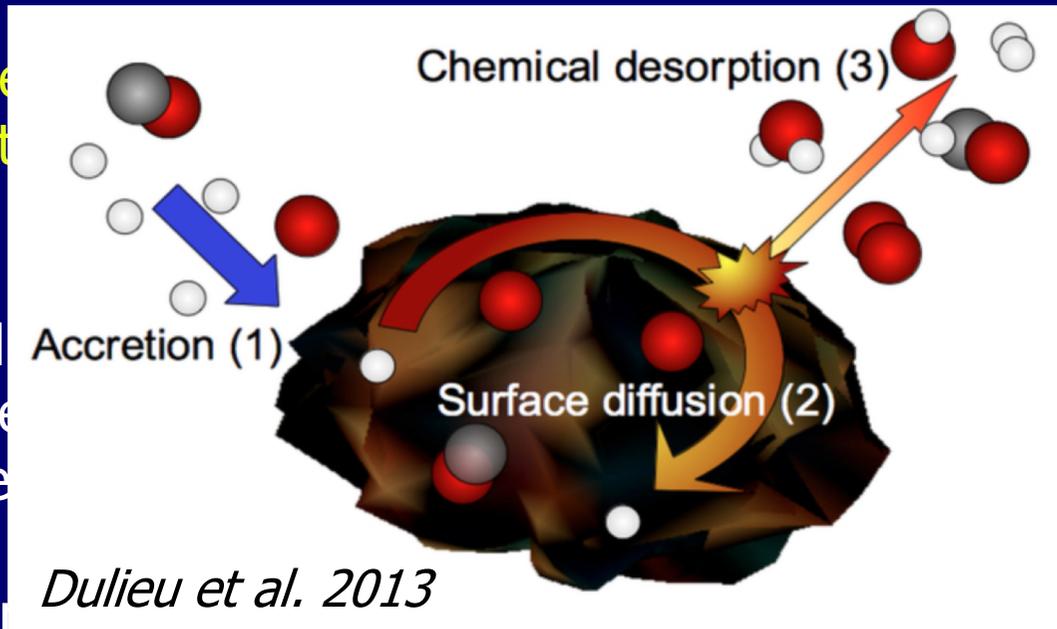
- Ion-molecule
- Neutral-neutral

- Ion induces d
- > creates e
- > effective

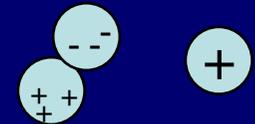
- At low temper

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- Simple molecules like CO or CS → ion-molecule chemistry,
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problem
(ic) important



es

ation of molecules.

Molecules in Space

2	3	4	5	6	7	8	9	10	11	12	13 atoms
H2	C3	c-C3H	C5	C5H	C6H	CH3C3N	CH3C4H	CH3C5N?	HC9N	CH3OC2H5	HC11N
AlF	C2H	l-C3H	C4H	l-H2C4	CH2CHCN	HCOOCH3	CH3CH2CN	(CH3)2CO			
AlCl	C2O	C3N	C4Si	C2H4	CH3C2H	CH3COOH?	(CH3)2O	NH2CH2COOH?			
C2	C2S	C3O	l-C3H2	CH3CN	HC5N	C7H	CH3CH2OH	CH3CH2CHO			
CH	CH2	C3S	c-C3H2	CH3NC	HCOCH3	H2C6	HC7N				
CH+	HCN	C2H2	CH2CN	CH3OH	NH2CH3	CH2OHCHO	C8H				
CN	HCO	CH2D+?	CH4	CH3SH	c-C2H4O	CH2CHCHO					
CO	HCO+	HCCN	HC3N	HC3NH+	CH2CHOH						
CO+	HCS+	HCNH+	HC2NC	HC2CHO							
CP	HOC+	HNCO	HCOOH	NH2CHO							
CSi	H2O	HNCS	H2CHN	C5N							
HCl	H2S	HOCO+	H2C2O	HC4N							
KCl	HNC	H2CO	H2NCN								
NH	HNO	H2CN	HNC3								
NO	MgCN	H2CS	SiH4								
NS	MgNC	H3O+	H2COH+								
NaCl	N2H+	NH3									
OH	N2O	SiC3									
PN	NaCN	C4									
SO	OCS										
SO+	SO2										
SiN	c-SiC2										
SiO	CO2										
SiS	NH2										
CS	H3+										
HF	SiCN										
SH	AlNC										
FeO(?)	SiNC										

More than 200 detected interstellar molecules as of October 2020 (www.cdms.de).
69 molecular detection in extragalactic systems.

A few important molecules

Mol.	Trans.	Abund.	Crit. dens. [cm ⁻³]	Comments
H ₂	1-0 S(1)	1	8x10 ⁷	Shock tracer
CO	J=1-0	8x10 ⁻⁵	3x10 ³	Low-density probe
OH	² Π _{3/2} ; J=3/2	3x10 ⁻⁷	1x10 ⁰	Magnetic field probe (Zeeman)
NH ₃	J,K=1,1	2x10 ⁻⁸	2x10 ⁴	Temperature probe
CS	J=2-1	1x10 ⁻⁸	4x10 ⁵	High-density probe
SiO	J=2-1		6x10 ⁵	Outflow shock tracer
H ₂ O	6 ₁₆ -5 ₂₃		1x10 ³	Maser
H ₂ O	1 ₁₀ -1 ₁₁	<7x10 ⁻⁸	2x10 ⁷	Warm gas probe
CH ₃ OH	7-6	1x10 ⁻⁷	1x10 ⁵	Dense gas/temperature probe
CH ₃ CN	19-18	2x10 ⁻⁸	2x10 ⁷	Temperature probe in Hot Cores

Crit. Dens.: $n_{\text{crit}} \sim A/\gamma$

Basics IV

Depletion of molecules on dust grains

In molecule's ref. frame, grains are moving at v_{therm} relative to molecules

$$E = 1/2 m v_{\text{therm}}^2 = 3/2 k_b T \Rightarrow v_{\text{therm}} = (3k_b T/m)^{1/2}$$

n grains sweeps out cylindrical volume in time Δt of
 $n(\pi a^2)v_{\text{therm}}\Delta t$ (a: grain radius)

Probability of molecule in volume V to be struck by grain in time Δt

$$P(\Delta t) = n(\pi a^2)v_{\text{therm}}\Delta t / V$$

Hence the collision time t_{coll} (for $P(\Delta t)V = 1$)

$$t_{\text{coll}} = 1/(n(\pi a^2)v_{\text{therm}}) = 1/(n_H \Sigma v_{\text{therm}}) \quad (n_H: \text{density}; \Sigma: \text{grain cross section})$$

For example CS: $v_{\text{therm}} \sim 5 \times 10^3 \text{ cm s}^{-1}$ at 10K, $n_H \sim 10^4 \text{ cm}^{-3}$, $\Sigma \sim 10^{-21} \text{ cm}^2$

$$t_{\text{coll}} \sim 6 \times 10^5 \text{ yr}$$

Depletion time-scale very short

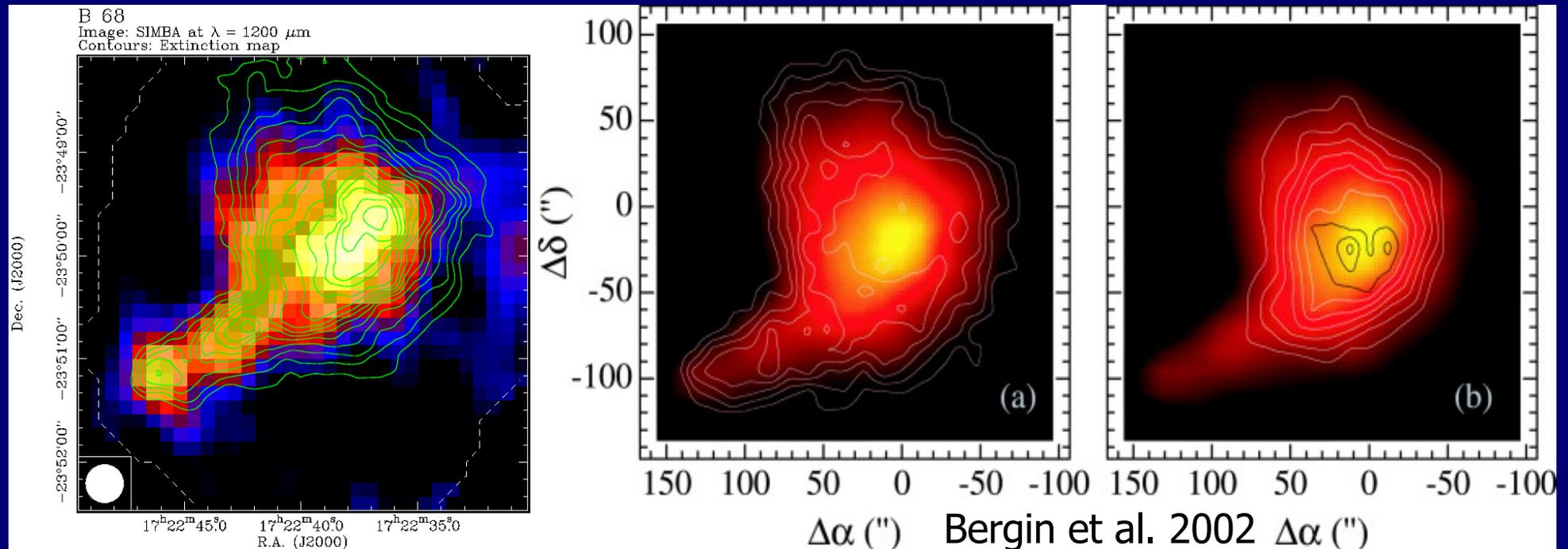
--> mechanisms for re-injecting molecules from grains important

Depletion example

1.2 mm Dust Continuum

$C^{18}O$

N_2H^+



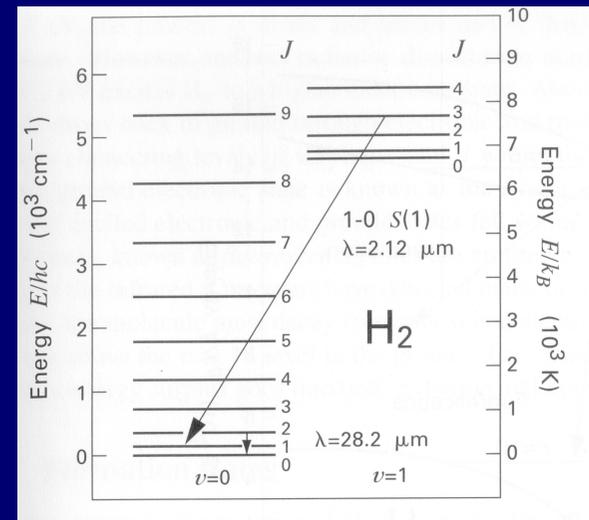
Possible mechanisms working against depletion:

- UV radiation (not working in dense cores)
- In small grain, heat from chemical grain surface reactions could raise temperature
- Kelvin-Helmholtz contraction and energy
- Ignited central protostar
- Shocks
- ...

Molecular Hydrogen (H₂)

- H₂ consists of 2 identical atoms → no electric dipole moment
- Rotationally excited H₂ has allowed quadrupole transitions $\Delta J = 2$
→ lowest rotational transition J=2-0 has energy change of 510 K

- Rotational energy for H₂:
Classical mechanics: $E_{\text{rot}} = J^2/2I$
(J: Angular momentum; I: Moment of inertia)
→ Small moment of inertia ($I=mr^2$)
→ large spread of energy levels

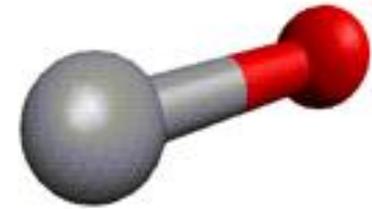


Stahler & Palla 2004

→ Cold clouds have to be observed other ways, e.g., CO

Carbon monoxide (CO)

- Forms through gas phase reactions.
- Strong binding energy of 11.1 eV
→ prevents much further destruction (self-shielding).



<http://www.cdms.de>

- Permanent dipole moment → strong emission at (sub)mm wavelengths.

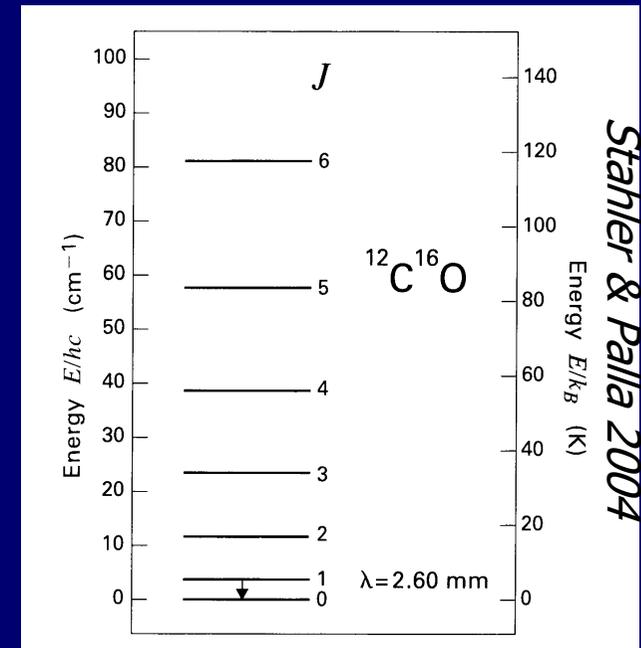
- Larger moment of inertia than H₂.
→ more closely spaced rotational ladder,
J=1 level at 4.8x10⁻⁴eV or 5.5K above ground

- In molecular clouds excitation mainly via collisions with H₂.
- Critical density for thermodynamic equilibrium with H₂ $n_{\text{crit}} = A/\gamma \sim 3 \times 10^3 \text{cm}^{-3}$.
(A: Einstein A coefficient; γ : collision rate with H₂)

- The level population follows a Boltzmann-law:

$$n_{J+1}/n_J = g_{J+1}/g_J \exp(-\Delta E/k_B T_{\text{ex}}) \quad (\text{for CO, the statistical weights } g_J = 2J + 1)$$

Excitation temperature T_{ex} is a measure for the level populations and equals the kinetic temperature T_{kin} if the densities are $> n_{\text{crit}}$.



Topics today

- The ISM, molecules and depletion
- Heating and cooling
- Radiation transfer and column density determination

Heating processes

UV radiation from stars

Energy injection from supernovae

Energy injection from outflows/jets

- Cosmic rays interact with HI and H₂
(consist mainly of relativistic protons accelerated within magnetized shocks produced by supernova-remnant--molecular cloud interactions)



- Interstellar radiation (diffuse field permeating interstellar space)
Mainly dissociates carbon (lower ionization potential than H₂)



- Photoelectric heating:
 - Heats grains which re-radiate in infrared regime
 - UV photons eject e⁻ from dust and these e⁻ heat surrounding gas via collisions

Cooling processes

- H & H₂ no dipole moment → no efficient coolant in cold molecular cloud
→ other coolants needed

--> Hydrogen collides with ambient atoms/molecules/grains
→ Cooling via these secondary constituents.



At higher densities other molecules come into play, e.g., H₂O.

→ CO the most effective coolant in molecular clouds.

- Collisions with gas atoms/molecules cause lattice vibrations on grain surfaces, that decay through the emission of infrared photons.

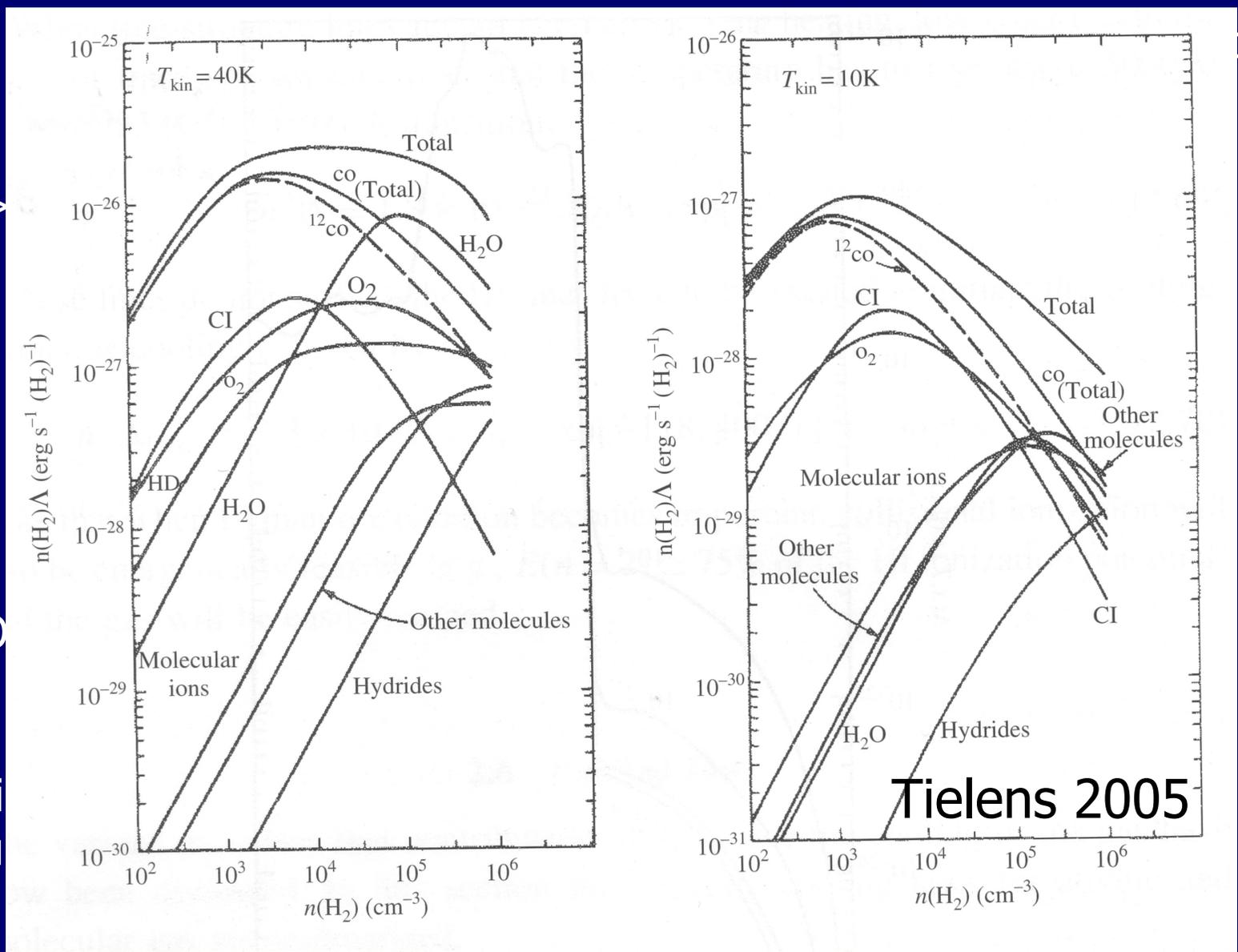
Cooling processes

- H &

->

-> CO

- Colli
SU



cloud

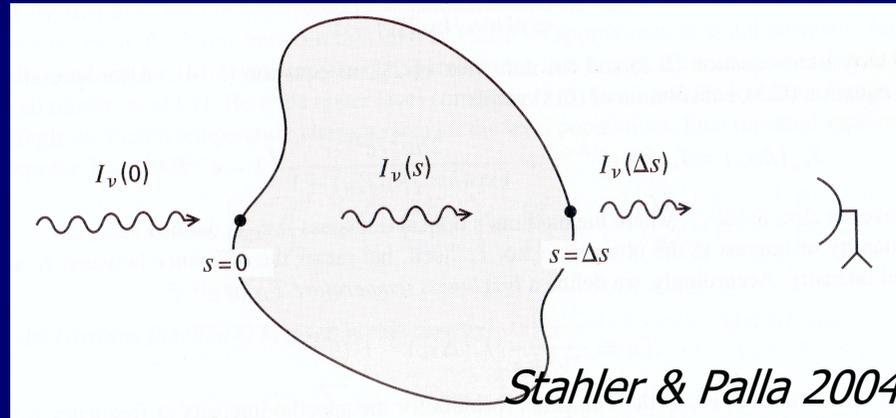
b)mm)
H₂O.

n

Topics today

- The ISM, molecules and depletion
- Heating and cooling
- Radiation transfer and column density determination

Radiation transfer I



$$dI_\nu = -\kappa_\nu I_{\nu,0} ds + \varepsilon_\nu ds$$

with the opacity

$$d\tau_\nu = -\kappa_\nu ds$$

and the source function

$$S_\nu = \varepsilon_\nu / \kappa_\nu$$

$$\Rightarrow dI_\nu / d\tau_\nu = I_{\nu,0} - S_\nu$$

Assuming a spatially constant source function \rightarrow radiation transfer equation

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

κ : absorption coef.
 ε : emission coef.

Radiation transfer II

The excitation temperature T_{ex} is defined via a Boltzmann distribution as

$$n_J/n_{J-1} = g_J/g_{J-1} \exp(-h\nu/kT_{\text{ex}})$$

with n_J and g_J the number density and statistical weights.

In case of rotational transitions

$$g_J = 2J + 1$$

J: rot. quantum
number

In thermal equilibrium

$$T_{\text{ex}} = T_{\text{kin}}$$

In a uniform molecular cloud the source function S_ν equals Planck function

$$S_\nu = B_\nu(T_{\text{ex}}) = 2h\nu^3/c^2 (\exp(h\nu/kT_{\text{ex}}) - 1)^{-1}$$

Radiation transfer III

Then the radiation transfer equation

$$\Rightarrow I_\nu = B_\nu(T_{\text{ex}}) (1 - e^{-\tau(\nu)}) + I_{\nu,0} e^{-\tau(\nu)}$$

In the Rayleigh-Jeans limits ($h\nu \ll kT$) B equals

$$B = 2k\nu^2/c^2 T \quad (\text{def. } \rightarrow T = c^2/(2k\nu^2) I_\nu)$$

And the radiation transfer equation using now the radiation temperature is

$$T_r = J_\nu(T_{\text{ex}}) (1 - e^{-\tau(\nu)}) + J_{\nu,0}(T_{\text{bg}}) e^{-\tau(\nu)}$$

with

$$J_\nu = h\nu/k (\exp(h\nu/kT) - 1)^{-1}$$

Molecular column densities I

To derive molecular column densities, 3 quantities are important:

- 1) Intensity T of the line
- 2) Optical depth τ of the line (observe isotopologues or hyperfine structure)
- 3) Partition function Q

The optical depth τ of a molecular transition can be expressed like

$$\tau = c^2/8\pi\nu^2 A_{ul}N_u (\exp(h\nu/kT) - 1) \phi$$

with the Einstein A_{ul} coefficient

$$A_{ul} = 64\pi^4\nu^3/(3c^3h) \mu^2 J_u/(2J_u-1)$$

and the line form function ϕ

$$\phi = c/\nu 2\text{sqrt}(\ln 2)/(\text{sqrt}(\pi)\Delta\nu)$$

Molecular column densities II

Using furthermore the radiation transfer eq. ignoring the background

$$T = J_\nu(T_{\text{ex}}) \tau (1 - e^{-\tau}) / \tau$$

And solving τ -equation for N_u , one gets

$$N_u = 3k/8\pi^3 \nu^{-1} / \mu^2 (2J_u - 1) / J_u \tau / (1 - e^{-\tau}) (T \Delta \nu \sqrt{\pi}) / (2\sqrt{\ln 2})$$

The last expression equals the integral $\int T dv$.

$$\rightarrow N_u \sim \tau / (1 - e^{-\tau}) \int T dv$$

The column density in the upper level N_u relates to the total column density N_{tot}

$$N_{\text{tot}} = N_u / g_u \exp(E_u / kT) Q$$

For linear molecule like CO, partition function Q approximated: $Q = kT/hB$.
(B : rotational constant)

However, for more complex molecules Q can become very complicated.

Conversion from CO to H₂ column densities

Classical way to derive conversion factors from CO to H₂ column densities:

- 1) Derive ratio between colour excess E_{B-V} and optical extinction A_V
$$A_V = 3.1 E_{B-V} \quad (\text{Savage and Mathis, 1979})$$
 - 2) The ratio $N(\text{H}_2)/E_{B-V}$: One can measure the H₂ column density, e.g., directly from UV Absorption lines.
 - 3) The ratio $N(\text{CO})/A_V$: In regions of molecular gas emission, one can estimate A_V by star counts in the Infrared regime
- ⇒ Combining these three ratios: CO → H₂ column densities.

Summary

- Main tools: Spectral line emission and thermal emission and extinction from dust (more on dust next week)
- Molecules interesting for themselves and chemistry
- However, also extremely useful to trace physical processes.
- Molecules deplete on grains at low temperatures
- Discussed main cooling and heating processes
- Discussed basic line radiation transfer and column density determination

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