Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

17.10 Today: Introduction & Overview (H.B.)

24.10 Physical processes I (H.B.)

31.10 no lecture – Reformationstag

07.11 Physcial processes II (H.B.)

14.11 Molecular clouds as birth places of stars (H.L.)

21.11 Molecular clouds (cont.), Jeans Analysis (H.B.)

28.11 Collapse models I (H.B.)

05.12 Collapse models II (T.H.)

12.12 Protostellar evolution (T.H.)

19.12 Pre-main sequence evolution & outflows/jets (T.H.)

09.01 Accretion disks I (T.H.)

16.01 Accretion disks II (T.H.)

23.01 High-mass star formation, clusters and the IMF (H.B.)

30.01 Planet formation (T.H.)

06.02 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_ws1718.html

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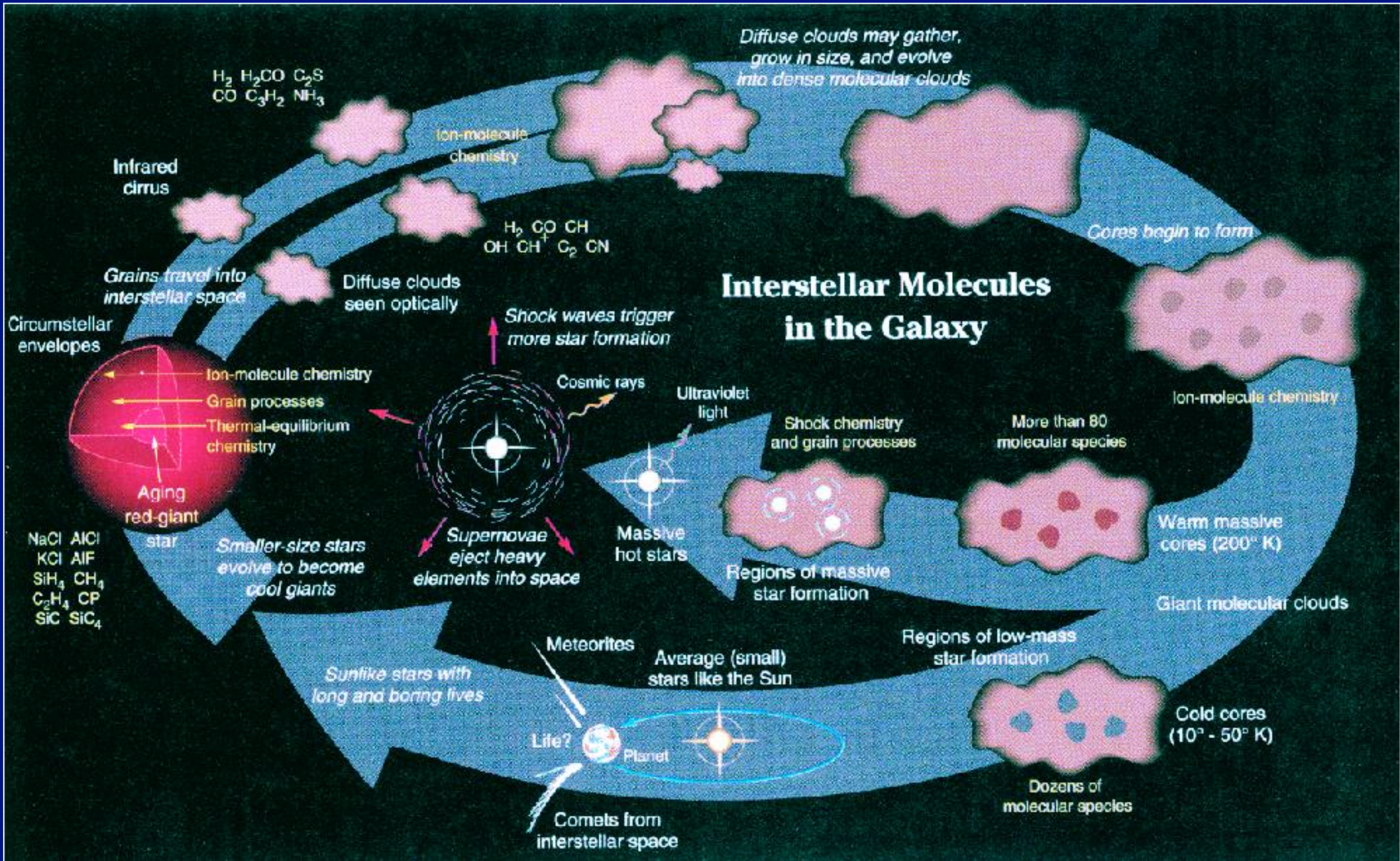
Topics today

- The ISM, molecules and depletion

- Heating and cooling

- Radiation transfer and column density determination

The cosmic cycle

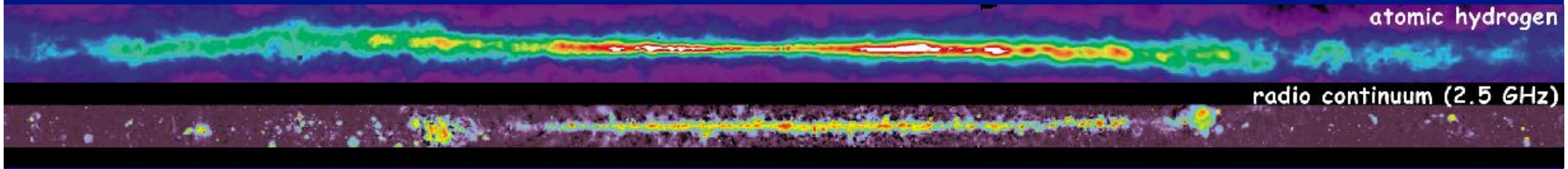


Properties of Molecular Clouds

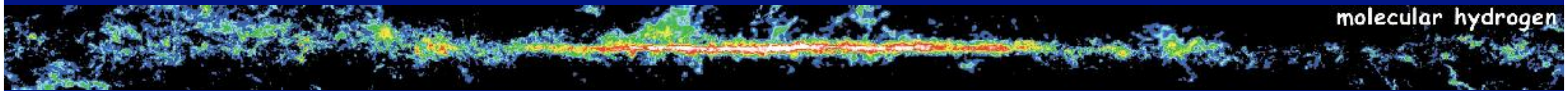
Type	n [cm^{-3}]	Size [pc]	T [K]	Mass [M_{sun}]
Giant Molecular Cloud	10^2	50	15	10^5
Dark Cloud Complex	$5x10^2$	10	10	10^4
Individual Dark Cloud	10^3	2	10	30
Dense low-mass cores	10^4	0.1	10	10
Dense high-mass cores	$>10^5$	0.1-1	10-30	100-10000

Basics

Neutral and ionized medium



Stars form in the dense molecular gas and dust cores



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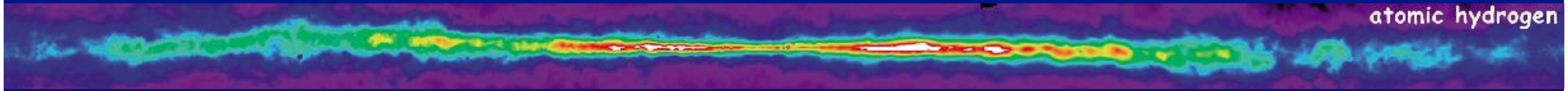
Most important astrophysical tools:

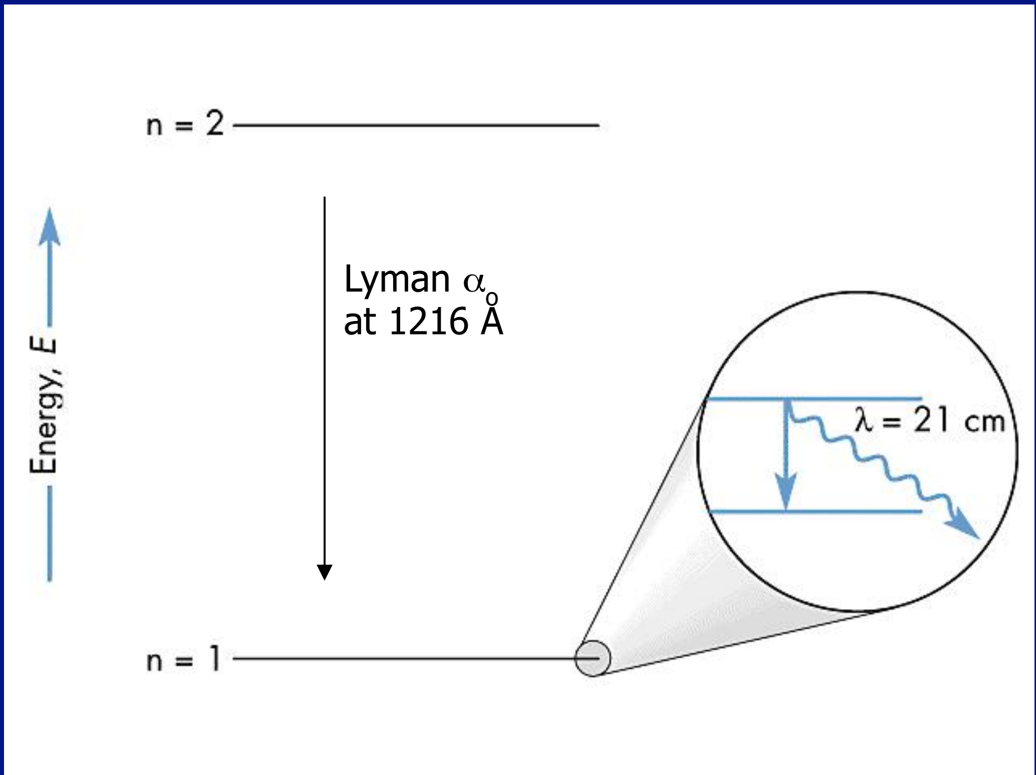
Spectral lines emitted by various molecules

Absorption and thermal emission from dust

The neutral atomic gas

Atomic Hydrogen

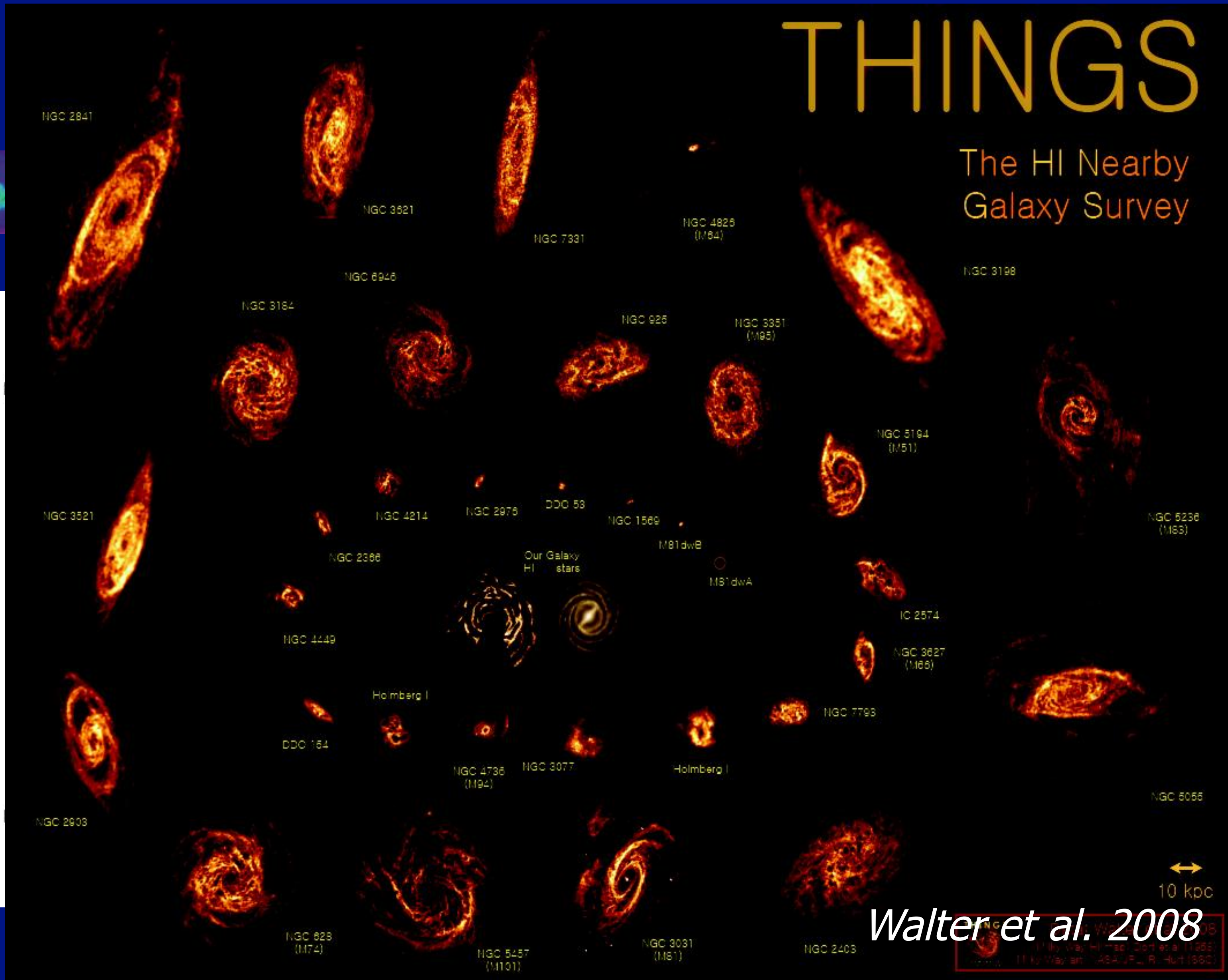




The 21cm line arises when the electron spin S flips from parallel (F=1) to antiparallel (F=0) compared to the Proton spin I.

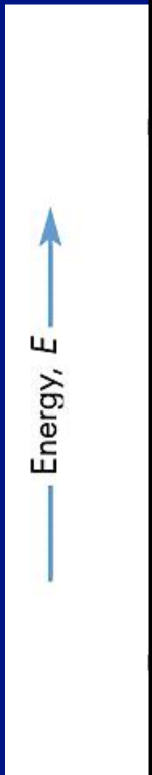
$\Delta E = 5.9 \times 10^{-5}$ eV

The neutral atomic gas



Walter et al. 2008

omic hydrogen



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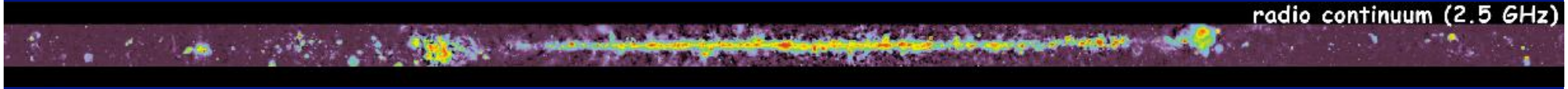
The Ionized gas

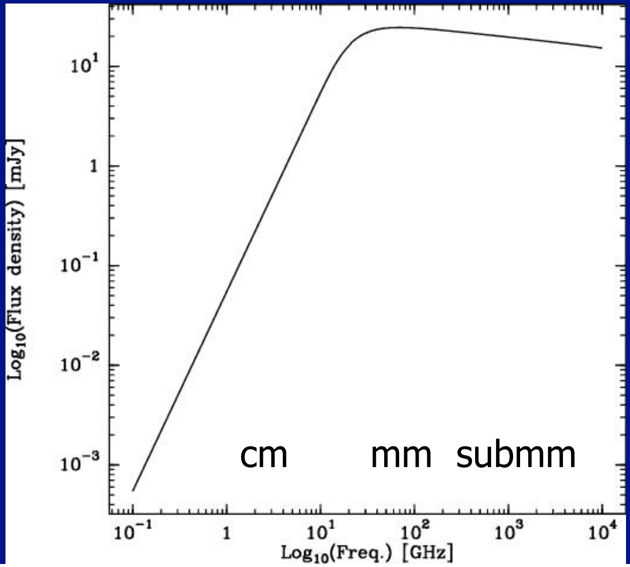
Ionized gas



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

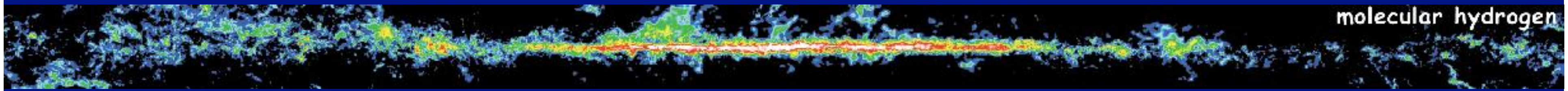
He/H	0.1
C/H	3.4×10^{-4}
N/H	6.8×10^{-5}
O/H	3.8×10^{-4}
Si/H	3.0×10^{-6}

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

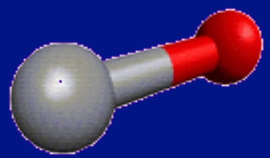


The Molecular ISM

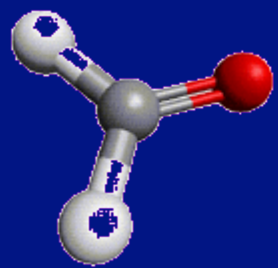
Molecular Hydrogen



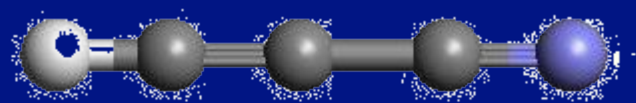
Carbon monoxide CO



Formaldehyde H_2CO



Cyanoacetyline HC_3N



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 ab-sorption of optical light by background stars
- 1960s: Detection of OH, NH_3 and H_2O 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:

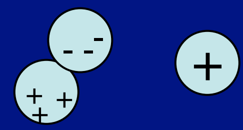
- Simultaneous collision with 3rd atom carrying away energy
  --> unlikely at the given low densities

- Form a molecule in excited state, and then radiating away energy
  --> probablility 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



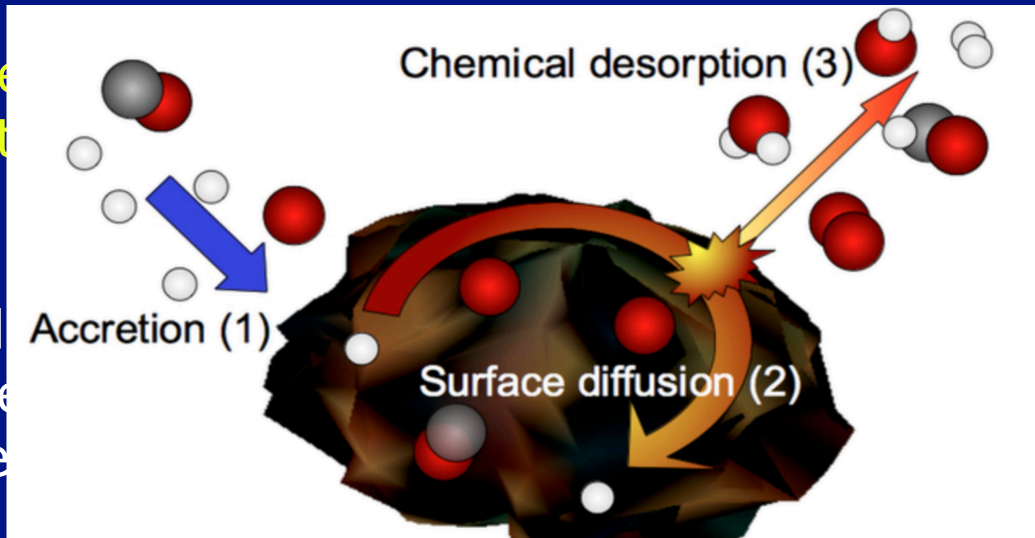
- At low temperatures such reactions account for large fraction of molecules.

- 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

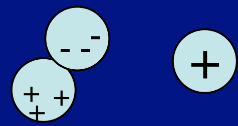
Molecular ISM Basics

- Ion-molecule ... oblem
- Neutral-neut ... ic) important



Dulieu et al. 2013

- Ion induces d ...
  --> creates ...
  --> effective ... es



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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										

About 200 detected interstellar molecules as of October 2017 (www.cdms.de).
61 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	$^2\Pi_{3/2}$;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_2O	6_{16}-5_{23}		$1x10^3$	Maser
H_2O	1_{10}-1_{11}	$<7x10^{-8}$	$2x10^7$	Warm gas probe
CH_3OH	7-6	$1x10^{-7}$	$1x10^5$	Dense gas/temperature probe
CH_3CN	19-18	$2x10^{-8}$	$2x10^7$	Temperature probe in Hot Cores

Basics IV

Depletion of molecules on dust grains

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

$E = 1/2\ mv^2_{therm} = 3/2\ k_bT \quad => v_{therm} = (3k_bT/m)^{1/2}$

n grains sweeps out cylindrical volume in time Δt of

$n(\pi a^2)v_{therm}\Delta t$ (a: grain radius)

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

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

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

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

For example CS: $v_{therm} \sim 5x10^3 cm\ s^{-1}$ at 10K, and $n_H \sim 10^4 cm^{-3}$

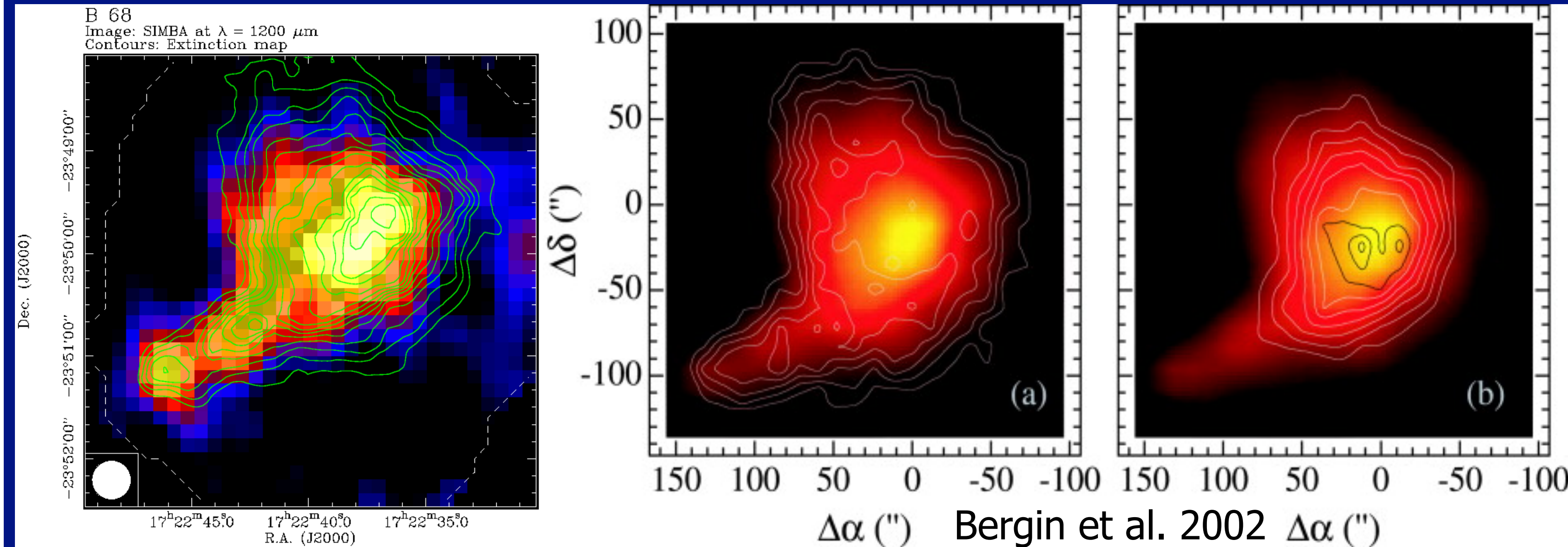
$t_{coll} \sim 6x10^5$ yr

Depletion time-scale very short

--> mechanisms for reinjecting 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
- …

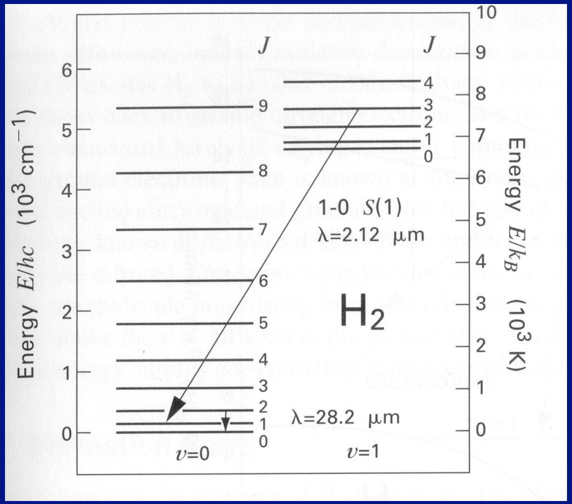
Molecular Hydrogen (H_2)

- H_2 consists of 2 identical atoms → no electric dipol moment

- Rotationally excited H_2 has allowed quadrupole transitions $\Delta J = 2$
  → lowest rotational transition J=2-0 has energy change of 510 K

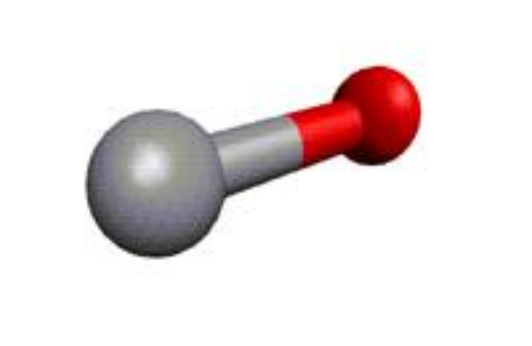
- Rotational energy for H_2:
  Classical mechanics: $E_{rot} = J^2/2I$
  (J: Angular momentum; I: Moment of inertia)

  → Small moment of inertia
  → large spread of energy levels



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

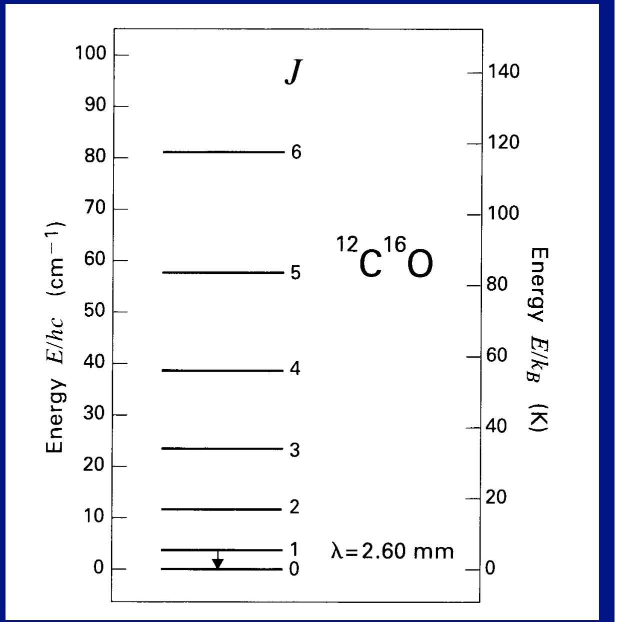
Carbon monxide (CO)



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

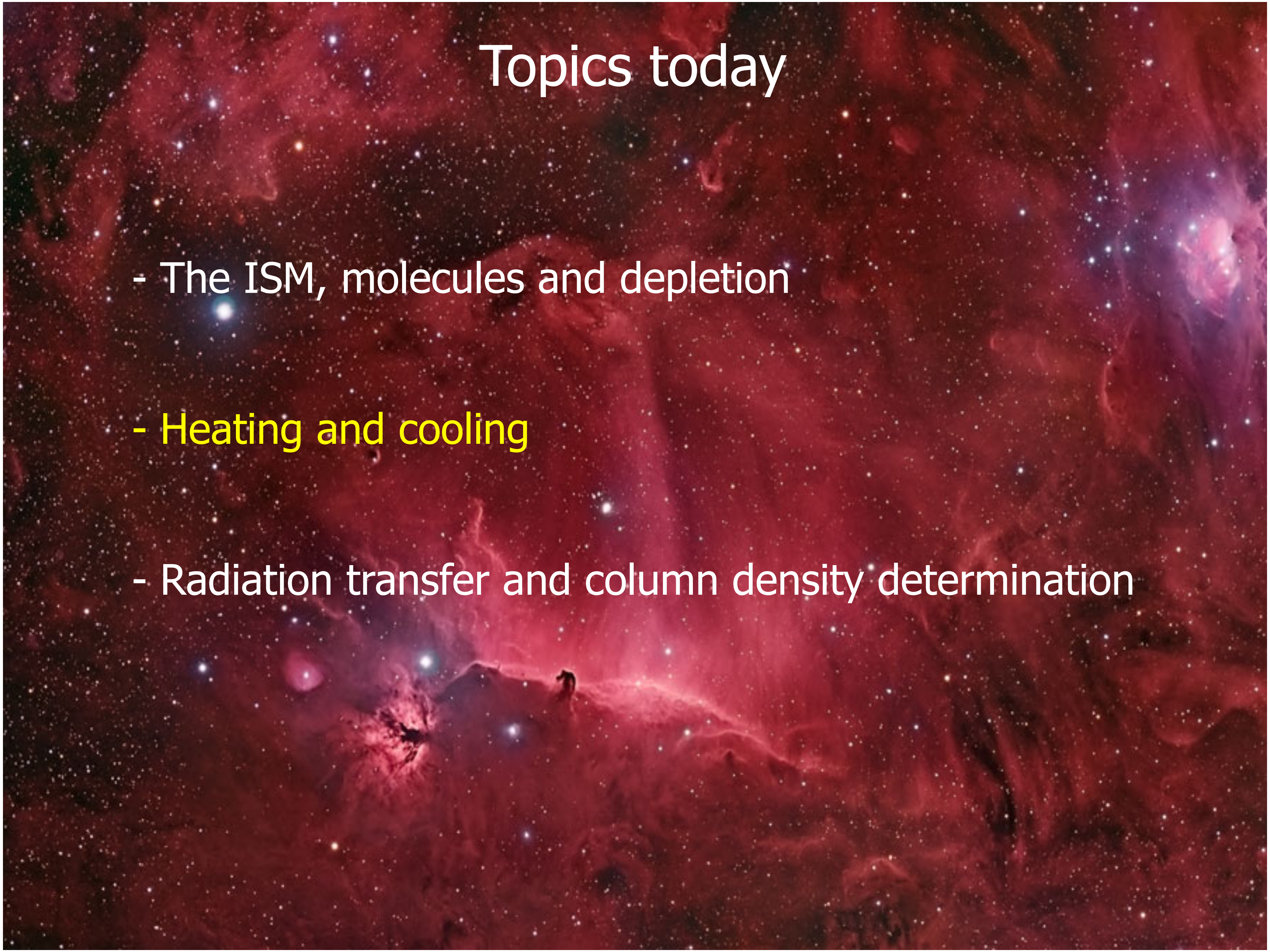
- Permanent dipole moment → strong emission at (sub)mm wavelengths.

- Larger moment of inertia than H_2.
  → more closely spaced rotational ladder,
  J=1 level at 4.8×10^{-4} eV or 5.5K above ground



- In molecular clouds excitation mainly via collisions with H_2.
- Critical density for thermodynamic equilibrium with H_2 $n_{crit} = A/\gamma \sim 3 \times 10^3 cm^{-3}$.
  (A: Einstein A coefficient; γ: collision rate with H_2)

- The level population follows a Boltzmann-law:
  $n_{J+1}/n_J = g_{J+1}/g_J \exp(-\Delta E/k_B T_{ex})$ (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_{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 H_2
(consist mainly of relativistic protons accelerated within magnetized shocks produced by supernova-remnant--molecular cloud interactions)

$p^+ + H_2 \rightarrow H_2^+ + e^- + p^+$ (dissociation → ion-molecule chemistry)

Interstellar radiation (diffuse field permeating interstellar space)
Mainly dissociates carbon (lower ionization potential than H_2)

$C + h\nu \rightarrow C^+ + e^-$ Electron disperses energy to ISM by collisions.

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 & H_2 no dipole moment → no efficient coolant in cold mol cloud
→ other coolants needed

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

$O + H \rightarrow O + H + h\nu$ collisional excitation (FIR)
$C^+ + H \rightarrow C^+ + H + h\nu$ fine structure excitation (FIR)
$CO + H_2 \rightarrow CO + H_2 + h\nu$ rotational excitation (radio/(sub)mm)
At higher densities other molecules come into play, e.g., H_2O.

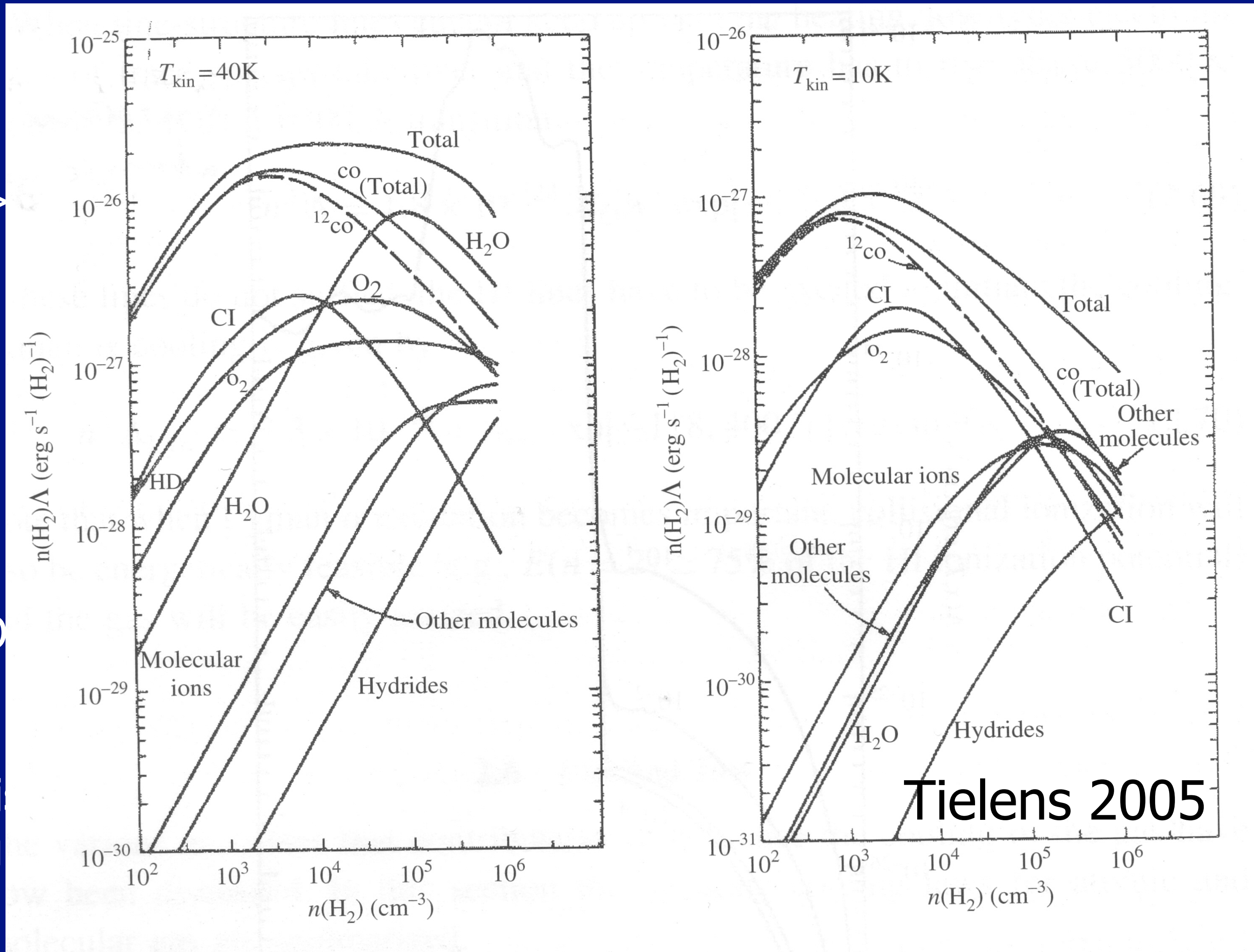
→ CO the most effective coolant in molecular clouds.

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

Cooling processes

- H &

-->



Tielens 2005

b)mm)

H_2O.

→ CO

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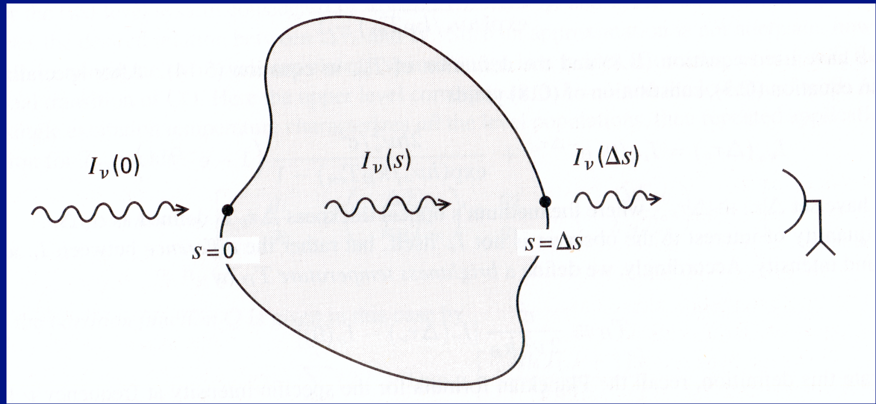
Radiation transfer I



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

κ: absorption coef.
ε: emission coef.

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 → radiation transfer equation

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

Radiation transfer II

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

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

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

$$T_{ex} = T_{kin}$$

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

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

Radiation transfer III

Then the radiation transfer equation

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

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

$B = 2k\nu^2/c^2\, T$ (def. $\rightarrow T = c^2/(2k\nu^2)\, I_\nu$)

And the radiation transfer equation using now the radiation temperature is

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

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

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

Molecular column densities II

Using furthermore the radiation transfer eq. ignoring the background

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

And solving this for N_u, one gets

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

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

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

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

For a linear molecule like CO, the partition function Q can be approximated to

$$Q = kT/hB.$$

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

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

Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

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