Sternentstehung - Star Formation

Winter term 2022/2023

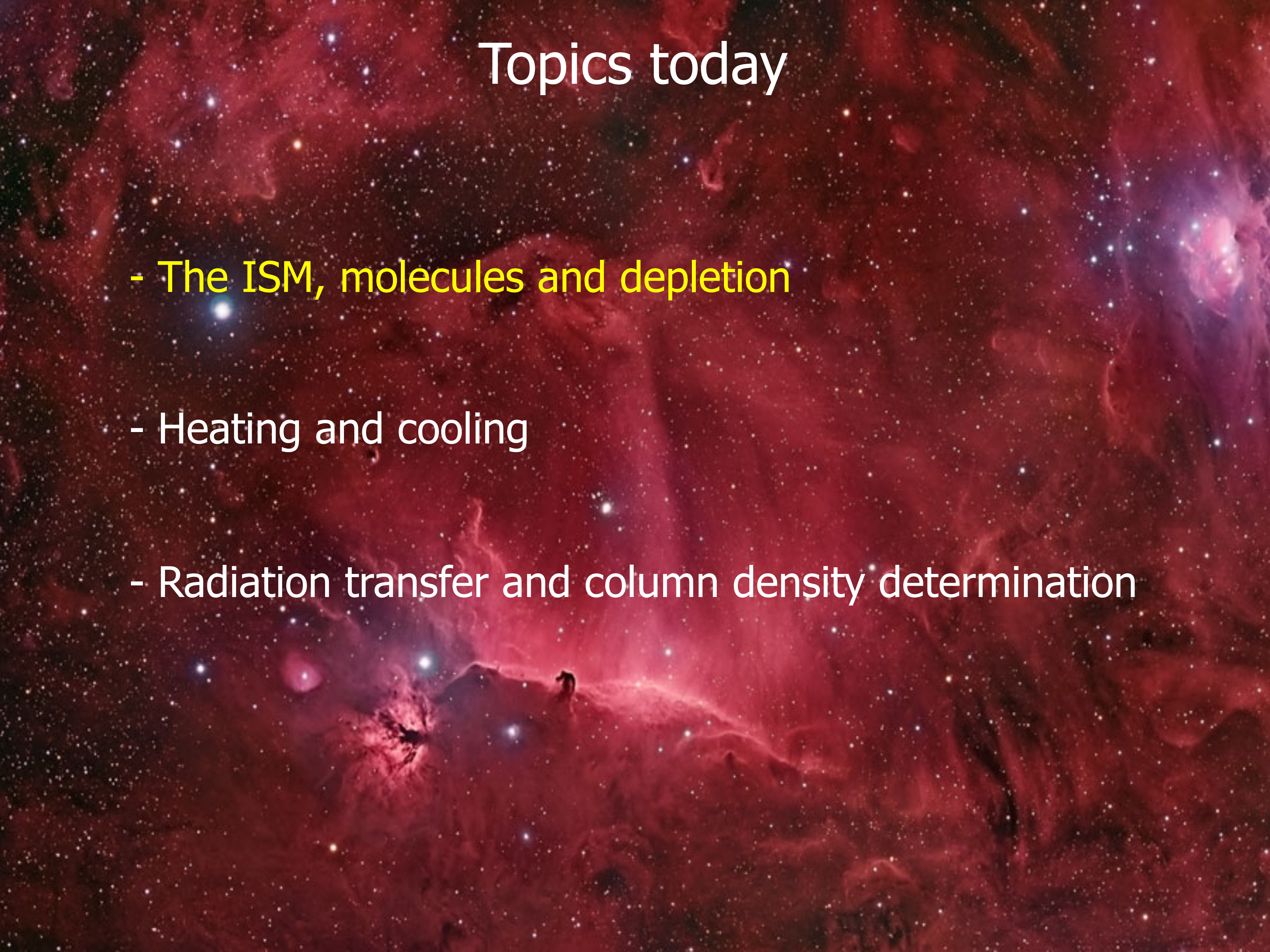
Henrik Beuther, Thomas Henning & Jonathan Henshaw

18.10 Today: Introduction & Overview	*(Beuther)*
25.10 Physical processes I	**(Beuther)**
08.11 Physcial processes II	(Beuther)
15.11 Molecular clouds as birth places of stars	(Henshaw)
22.11 Molecular clouds (cont.), Jeans Analysis	(Henshaw)
29.11 Collapse models I	(Beuther)
06.12 Collapse models II	(Henning)
13.12 Protostellar evolution	(Beuther)
20.12 Pre-main sequence evolution & outflows/jets	(Beuther)
10.01 Accretion disks I	(Henning)
17.01 Accretion disks II	(Henning)
24.01 High-mass star formation, clusters and the IMF	(Henshaw)
31.01 Extragalactic star formation	(Henning)
07.02 Planetarium@HdA, outlook, questions	
13.02 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_ws2223.html

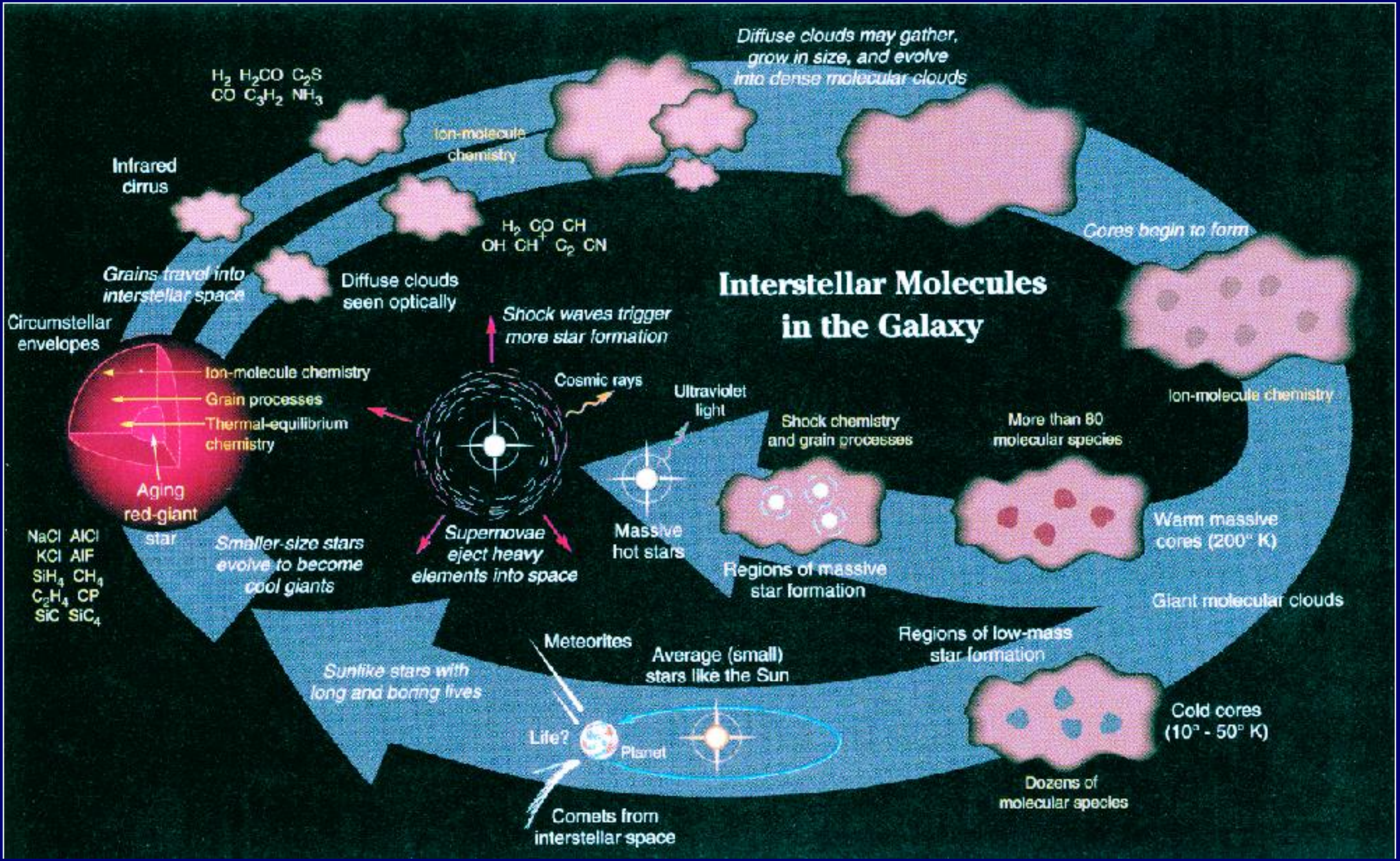
beuther@mpia.de, henning@mpia.de , henshaw@mpia.de



Topics today

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

The cosmic cycle



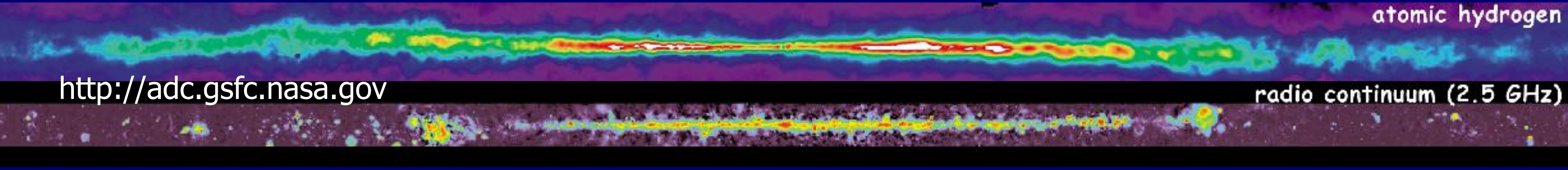
http://www.astro.uni-koeln.de

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	5×10^2	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

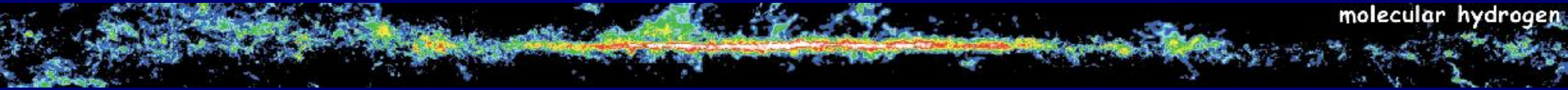
Basics

Neutral and ionized medium



http://adc.gsfc.nasa.gov

Stars form in the dense molecular gas and dust cores



↓

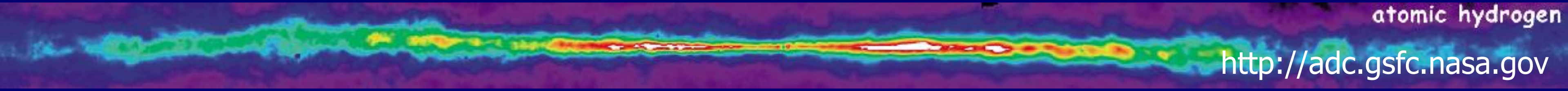
__Most important astrophysical tools:__

Spectral lines emitted by various molecules

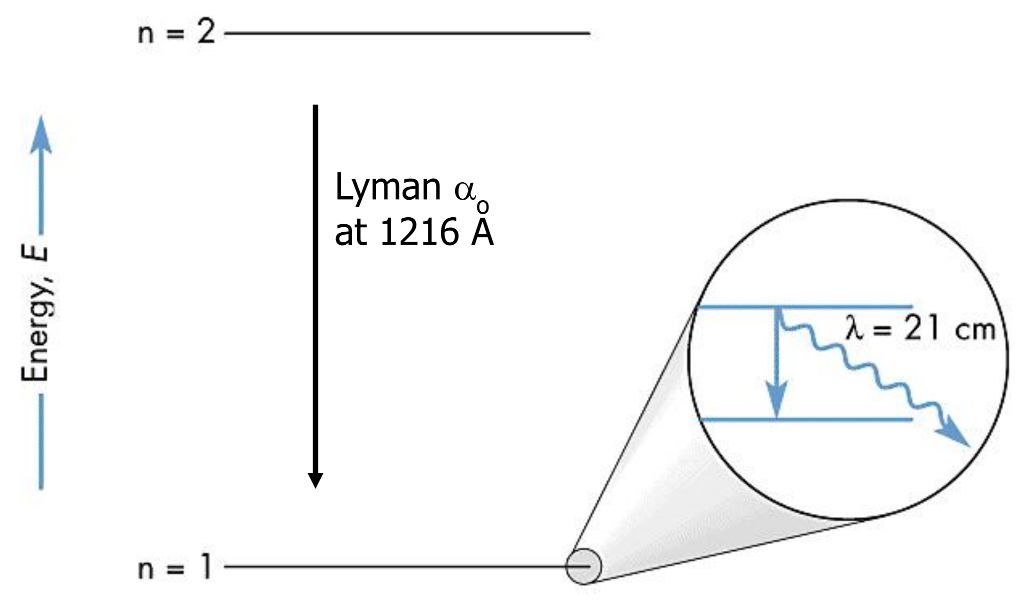
Absorption and thermal emission from dust

The Interstellar Medium I

Atomic Hydrogen



http://adc.gsfc.nasa.gov

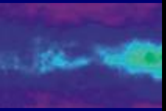


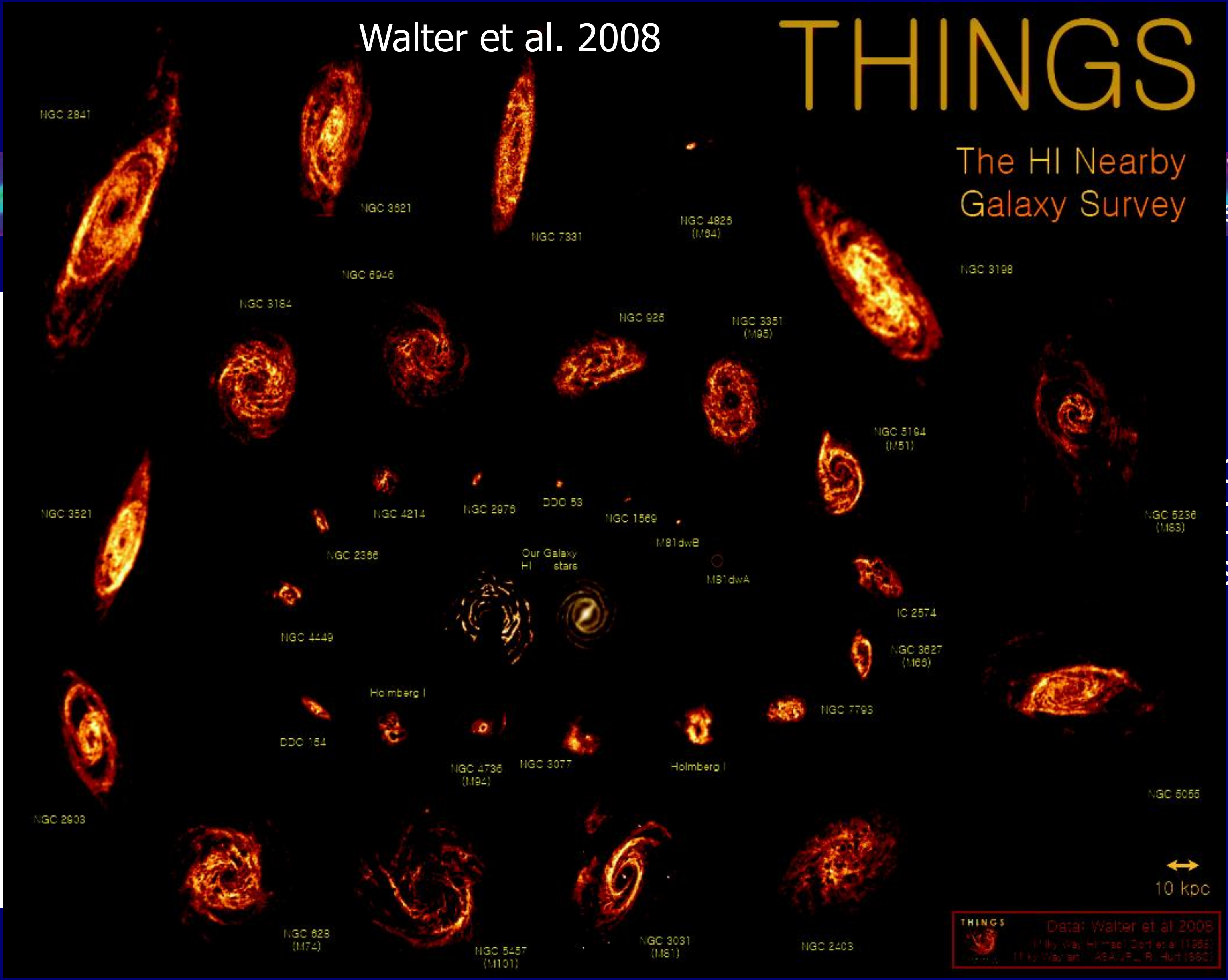
21cm line:

electron spin S flip from parallel (F=1) to antiparallel (F=0) compared to the Proton spin I.

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

The Interstellar Medium I

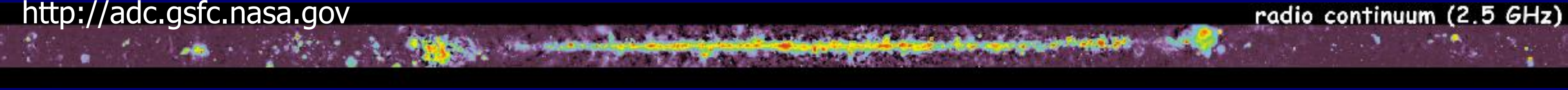



Walter et al. 2008

parallel
0)
spin I.

The Ionized gas

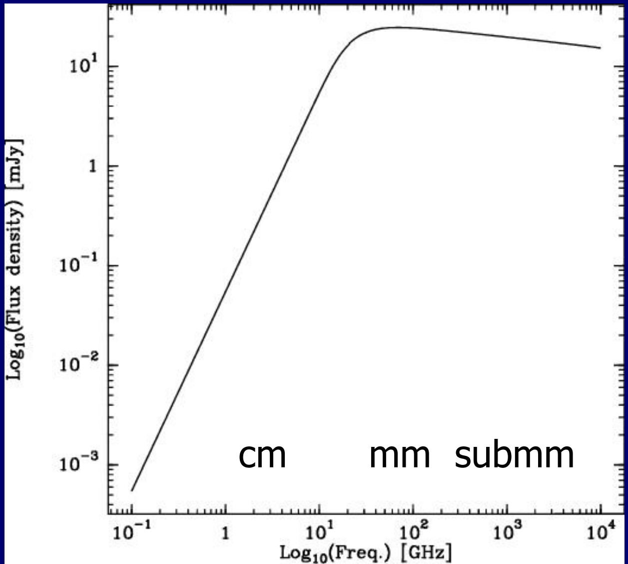
Ionized gas



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

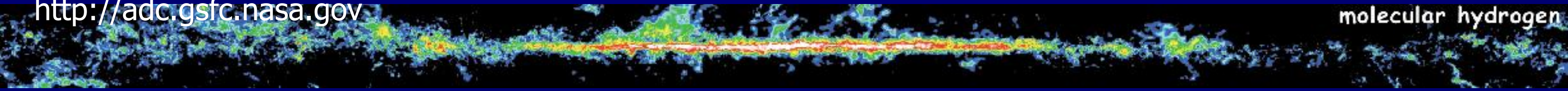
He/H	0.1
C/H	3.4×10^{-4}
N/H	6.8×10^{-5}
O/H	3.8×10^{-4}
Si/H	3.0×10^{-6}

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



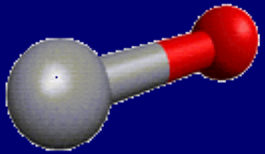
The Molecular ISM

Molecular Hydrogen



http://adc.gsfc.nasa.gov

Carbon monoxide CO



Formaldehyde H_2CO

http://www.cdms.de

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 absorption of optical light from 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

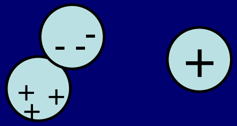
Possibilities:

- 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
  --> probalility 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.

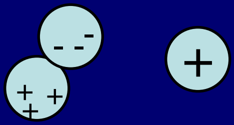
- However, not enough ions to account for large H_2 abundances
  --> grain surface chemistry important

- Simple molecules like CO or CS → ion-molecule chemistry,
- More complex molecules → grain surface chemistry important

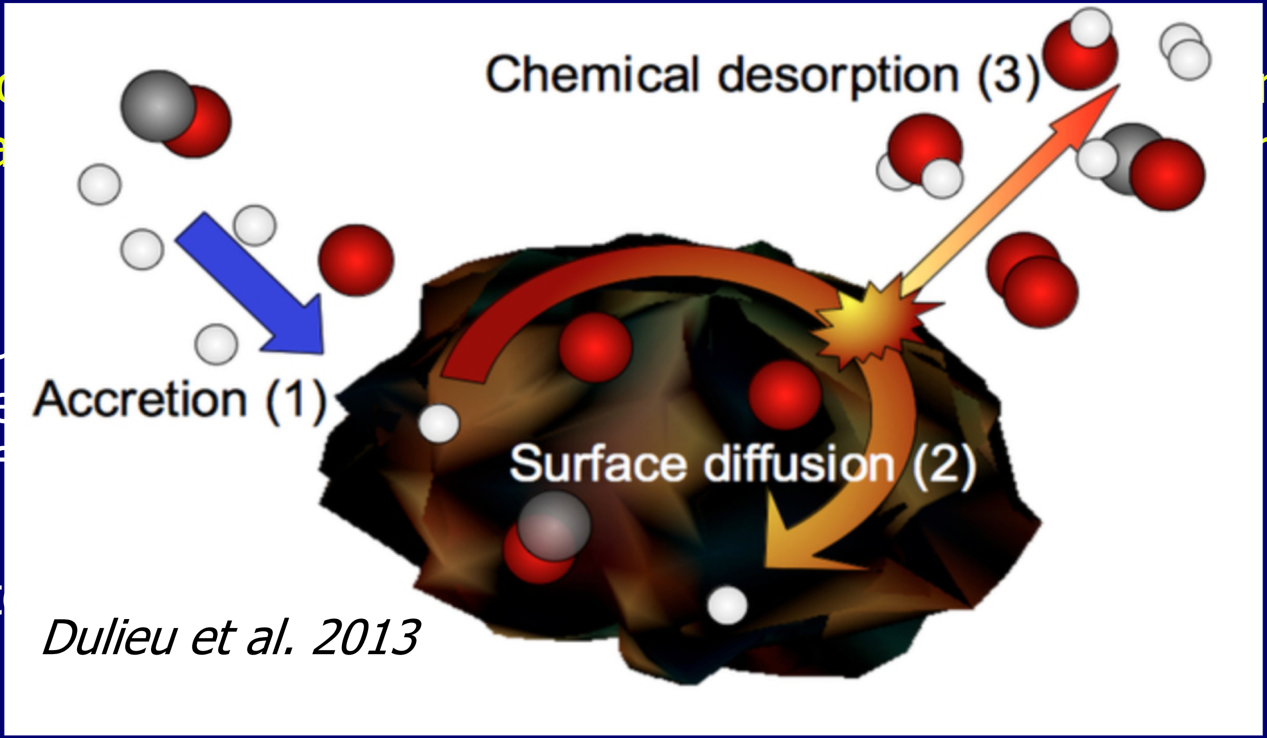
Molecular ISM Basics

- Ion-mo m
- Neutra mportant

- Ion indu
  - --> cre
  - --> eff



- At low t of molecules.



Dulieu et al. 2013

- 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

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 270 detected interstellar molecules as of October 2022 (www.cdms.de).
73 molecular detection in extragalactic systems.

A few important molecules

Mol.	Trans.	Abund.	Crit. dens. [cm^{-3}]	Comments
H_2	1-0 S(1)	1	8×10^{7}	Shock tracer
CO	J=1-0	8×10^{-5}	3×10^{3}	Low-density probe
OH	$^2\Pi_{3/2}$;J=3/2	3×10^{-7}	1×10^{0}	Magnetic field probe (Zeeman)
NH_3	J,K=1,1	2×10^{-8}	2×10^{4}	Temperature probe
CS	J=2-1	1×10^{-8}	4×10^{5}	High-density probe
SiO	J=2-1		6×10^{5}	Outflow shock tracer
H_2O	$6_{16}-5_{23}$		1×10^{3}	Maser
H_2O	$1_{10}-1_{11}$	$<7\times10^{-8}$	2×10^{7}	Warm gas probe
CH_3OH	7-6	1×10^{-7}	1×10^{5}	Dense gas/temperature probe
CH_3CN	19-18	2×10^{-8}	2×10^{7}	Temperature probe in Hot Cores

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

Basics IV

Depletion of molecules on dust grains

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

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

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

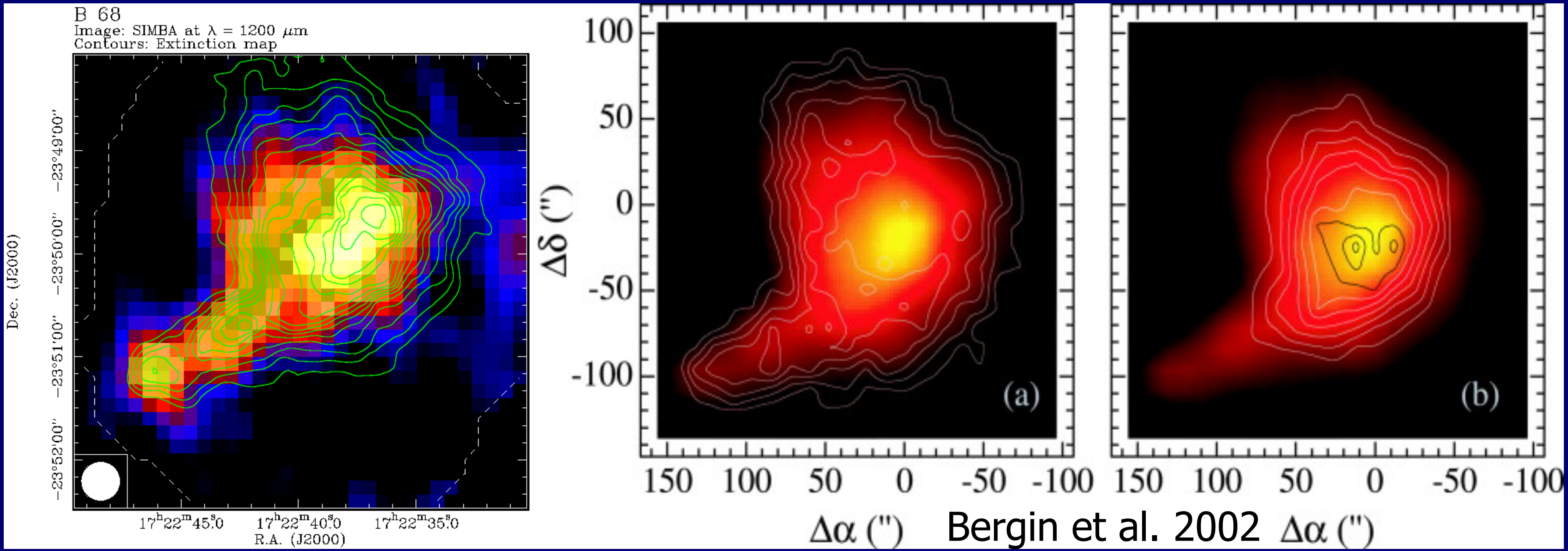
Probability of molecule in volume V to be struck by grain in time Δt
$P(\Delta t) = n(\pi a^2)v_{therm}\Delta t\ /V$

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: grain cross section)

For example CS: $v_{therm} \sim 5\times10^3$cm s^{-1} at 10K, $n_H \sim 10^4$cm^{-3}, $\Sigma \sim 10^{21}$cm^2
$t_{coll} \sim 6\times10^5$ 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^+

Bergin et al. 2002

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
- ...

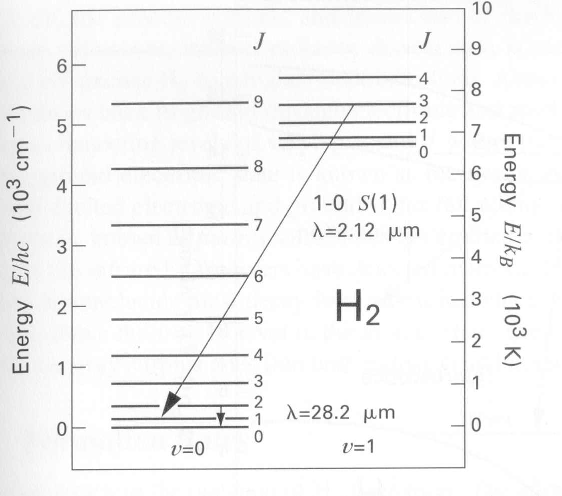
Molecular Hydrogen (H_2)

- H_2 consists of 2 identical atoms → no electric dipole 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)

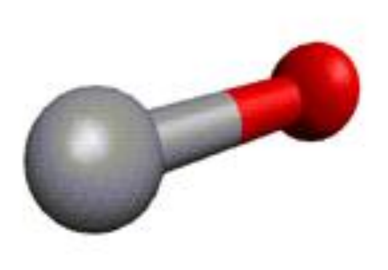
  → Small moment of inertia ($I=mr^2$)
  → large spread of energy levels



Stahler & Palla 2004

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

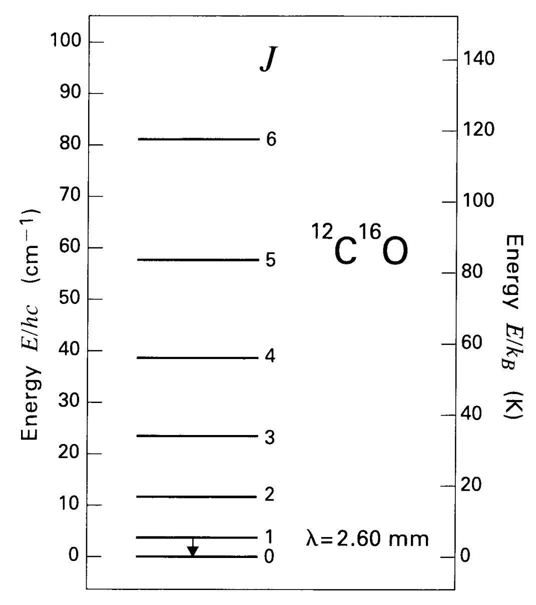
Carbon monxide (CO)



http://www.cdms.de

- 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.

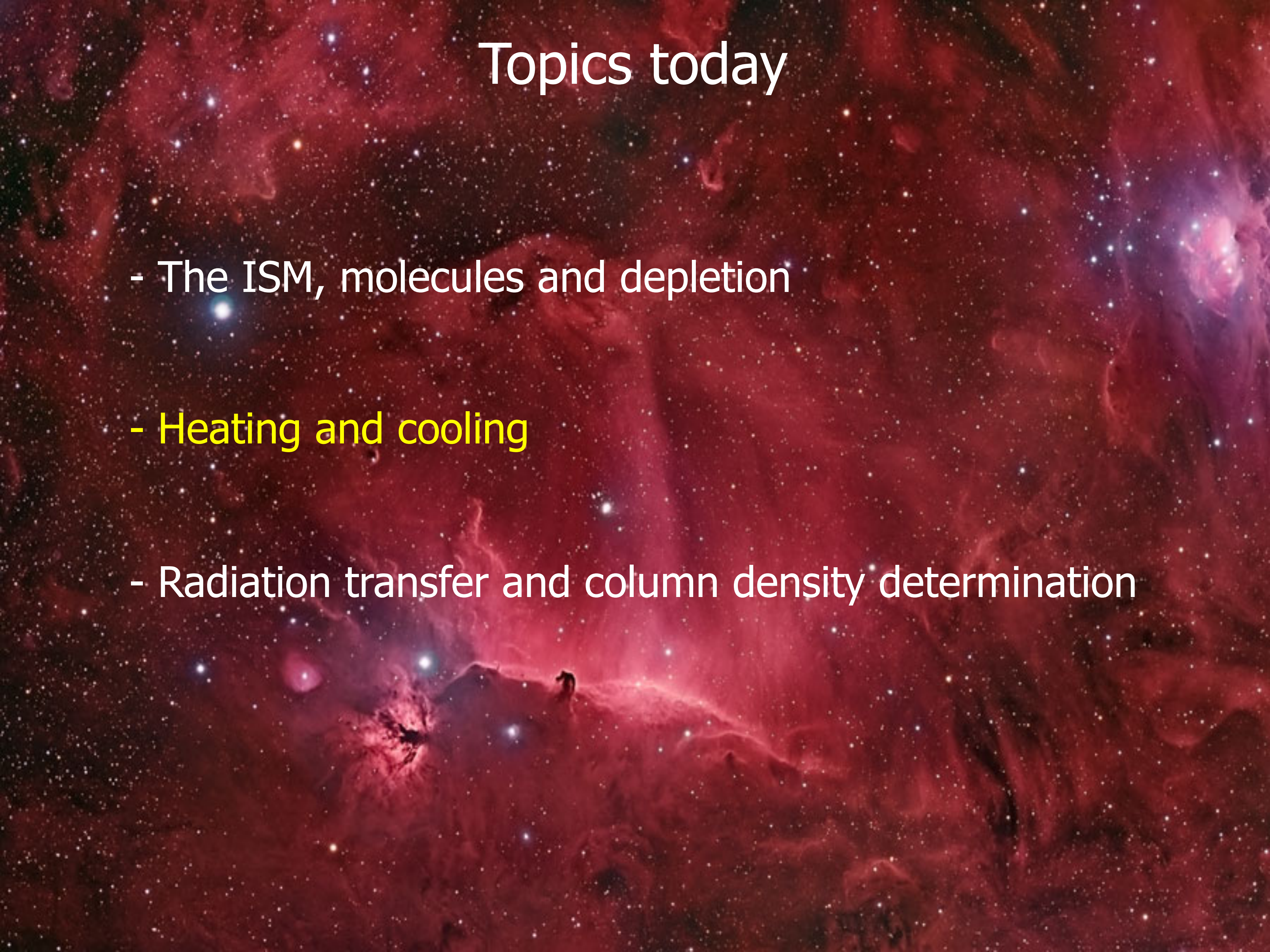


Stahler & Palla 2004

- 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 $n_{crit} = A/\gamma \sim 3 \times 10^3 \mathrm{cm}^{-3}$.
  (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)

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

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

  $C + h\nu \dashrightarrow C^+ + e^-$ 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 molecular 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.

→ dust very efficient coolant

Cooling processes

- H & … ud

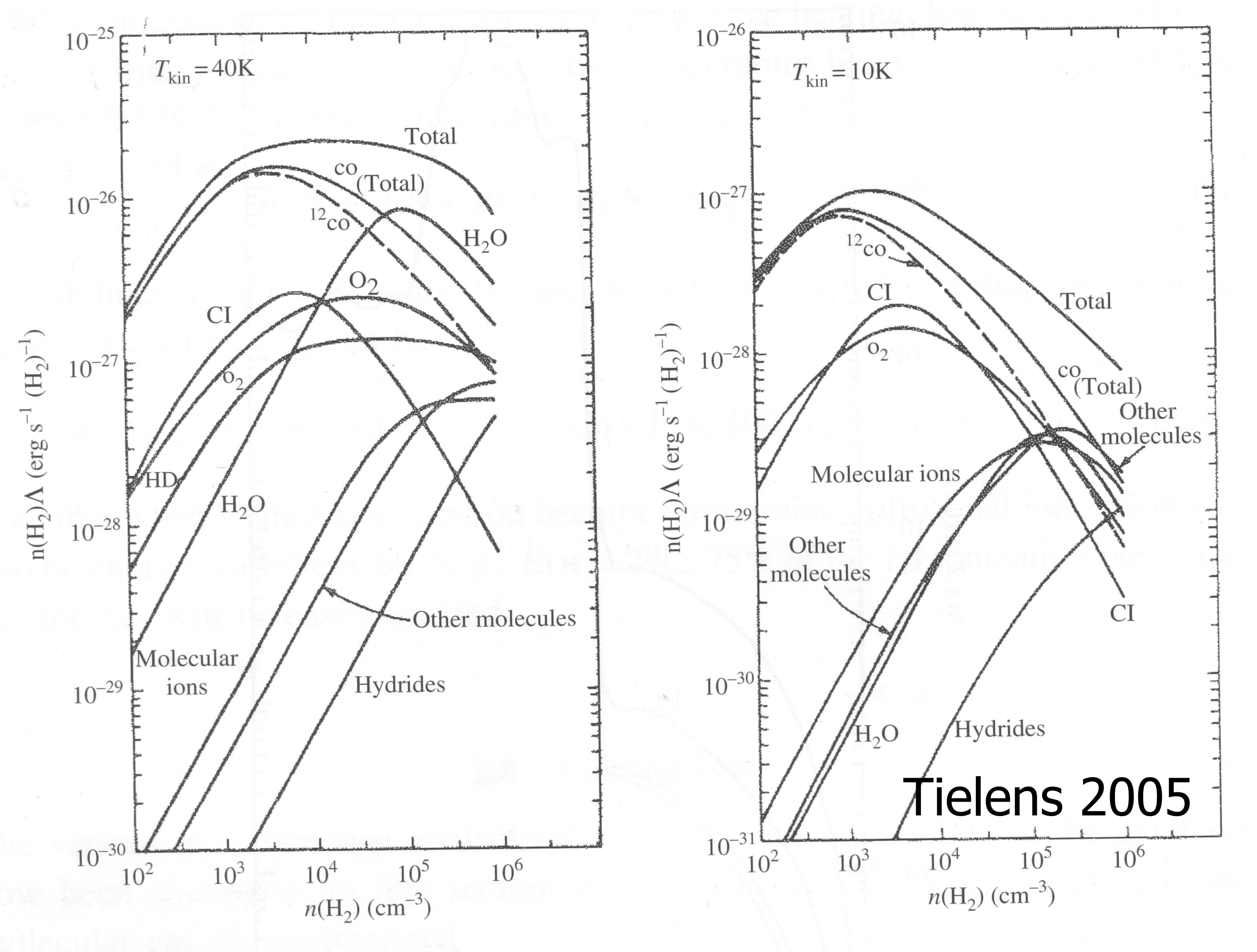
-->

mm)

O.

→ CO

- Coll
  su



Tielens 2005

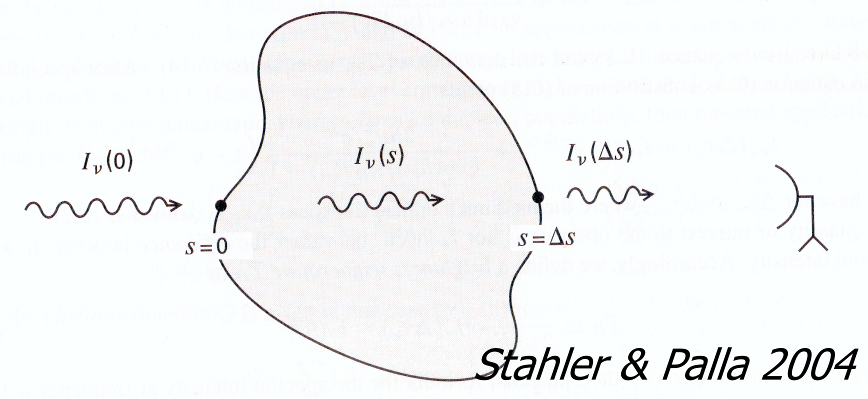
Topics today

- The ISM, molecules and depletion

- Heating and cooling

- Radiation transfer and column density determination

Radiation transfer I



Stahler & Palla 2004

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

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

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

And the radiation transfer equation using now the radiation temperature is

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

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 τ -equation for N_u, one gets

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

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}

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

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 H_2 column densities

Classical way to derive conversion factors from CO to H_2 column densities:

1) Derive ratio between colour excess $E_{B\text{-}V}$ and optical extinction A_v
   $A_v = 3.1\, E_{B\text{-}V}$ (Savage and Mathis, 1979)

2) The ratio $N(H_2)/E_{B\text{-}V}$: One can measure the H_2 column density, e.g., directly from UV Absorption lines.

3) The ratio $N(CO)/A_v$: In regions of molecular gas emission, one can estimate A_v by star counts in the Infrared regime

⇒ Combining these three ratios: CO → H_2 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

Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning & Jonathan Henshaw

18.10 Today: Introduction & Overview	*(Beuther)*
25.10 Physical processes I	*(Beuther)*
08.11 Physcial processes II	**(Beuther)**
15.11 Molecular clouds as birth places of stars	(Henshaw)
22.11 Molecular clouds (cont.), Jeans Analysis	(Henshaw)
29.11 Collapse models I	(Beuther)
06.12 Collapse models II	(Henning)
13.12 Protostellar evolution	(Beuther)
20.12 Pre-main sequence evolution & outflows/jets	(Beuther)
10.01 Accretion disks I	(Henning)
17.01 Accretion disks II	(Henning)
24.01 High-mass star formation, clusters and the IMF	(Henshaw)
31.01 Extragalactic star formation	(Henning)
07.02 Planetarium@HdA, outlook, questions	
13.02 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_ws2223.html

beuther@mpia.de, henning@mpia.de , henshaw@mpia.de

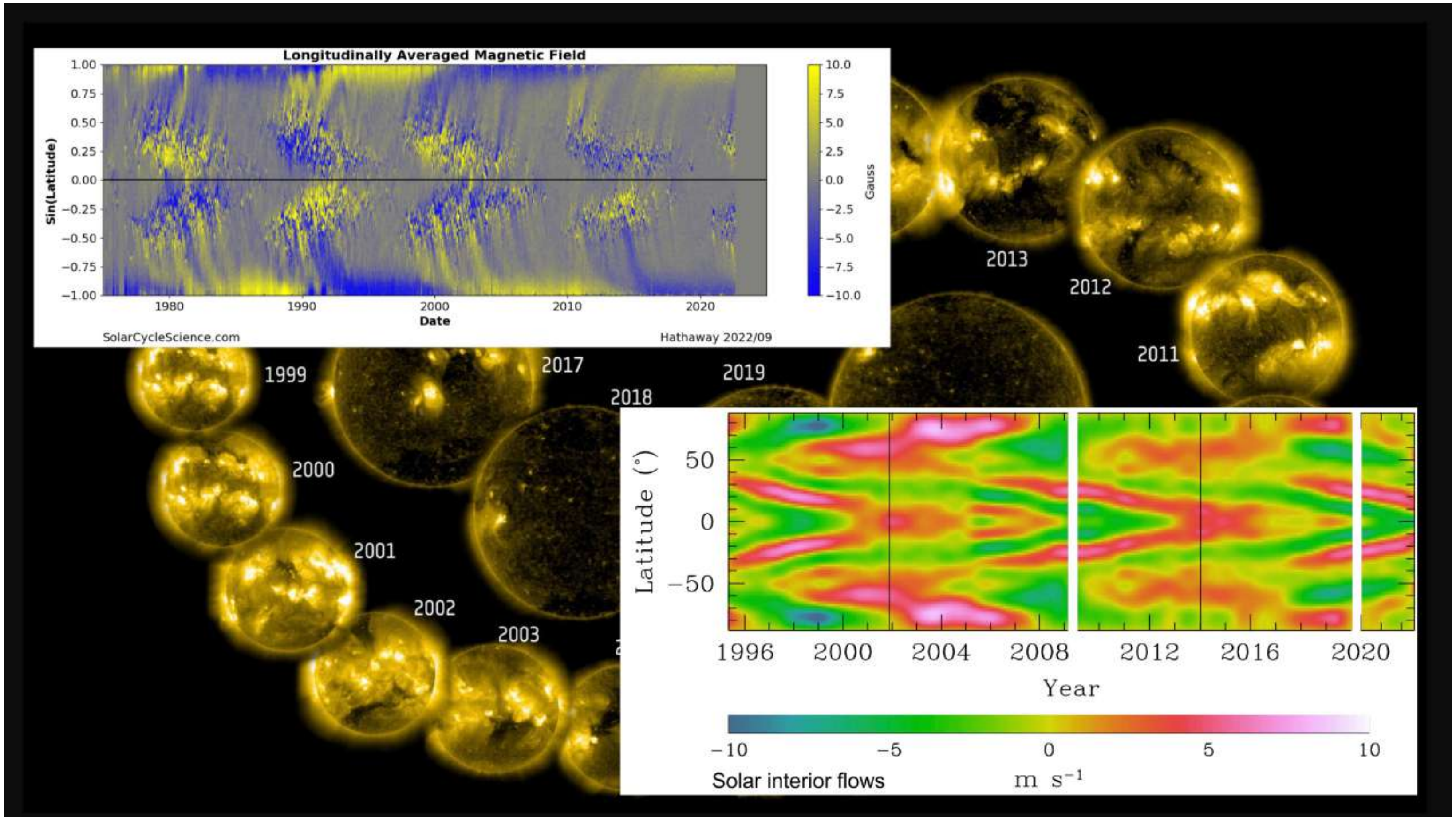
Heidelberg Joint Astronomical Colloquium

Winter Semester 2022 — Tuesday October 25th, 16:00

Main Lecture Theatre, Philosophenweg 12

Sarbani Basu (Yale University, USA):

The Sun as a variable Star



Those unable to attend the colloquium in person are invited to participate online through Zoom.
More information is given on HePhySTO: https://www.physik.uni-heidelberg.de/hephysto/