Outflows and Jets: Theory and Observations

Summer term 2011

Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html
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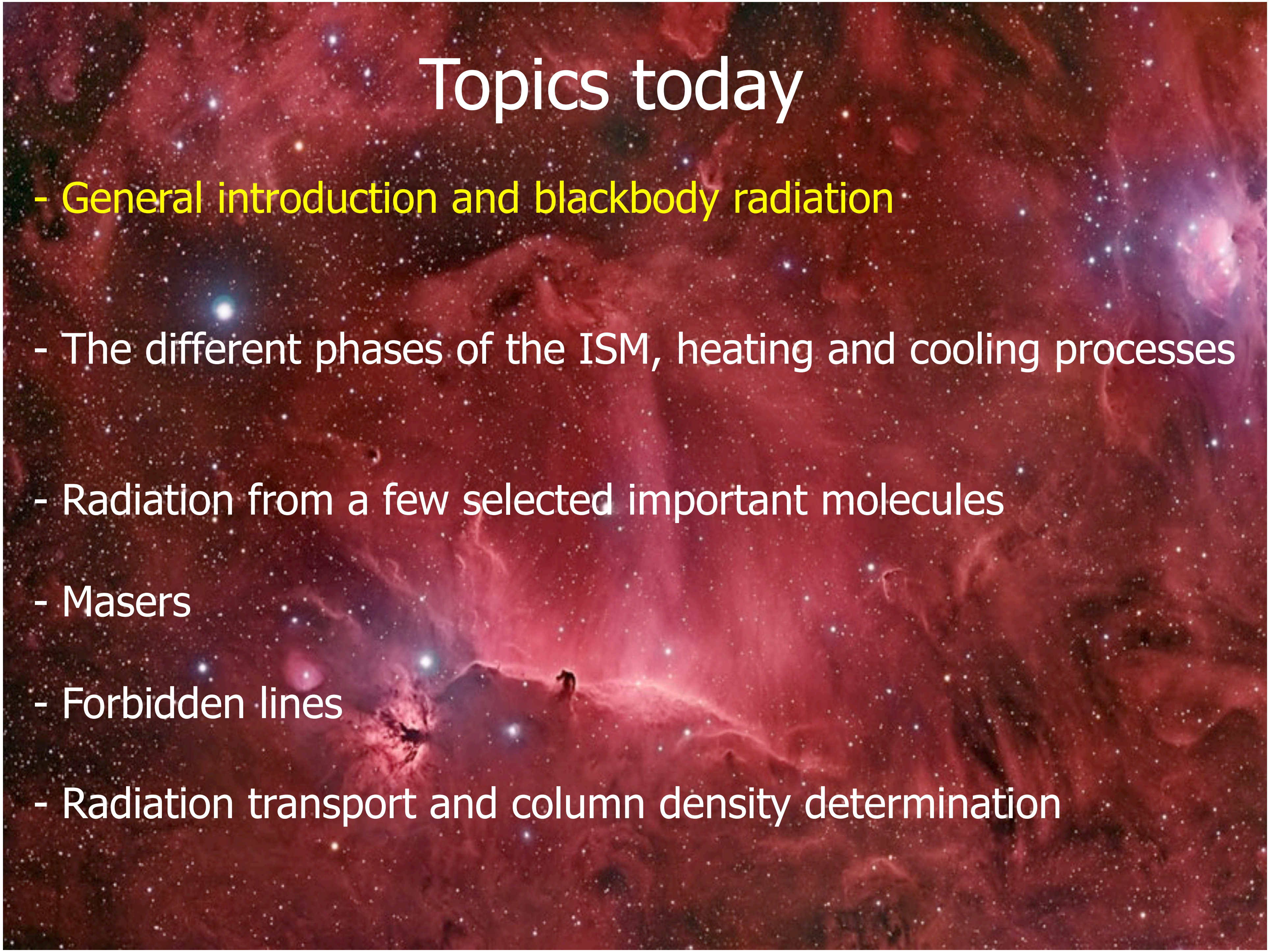
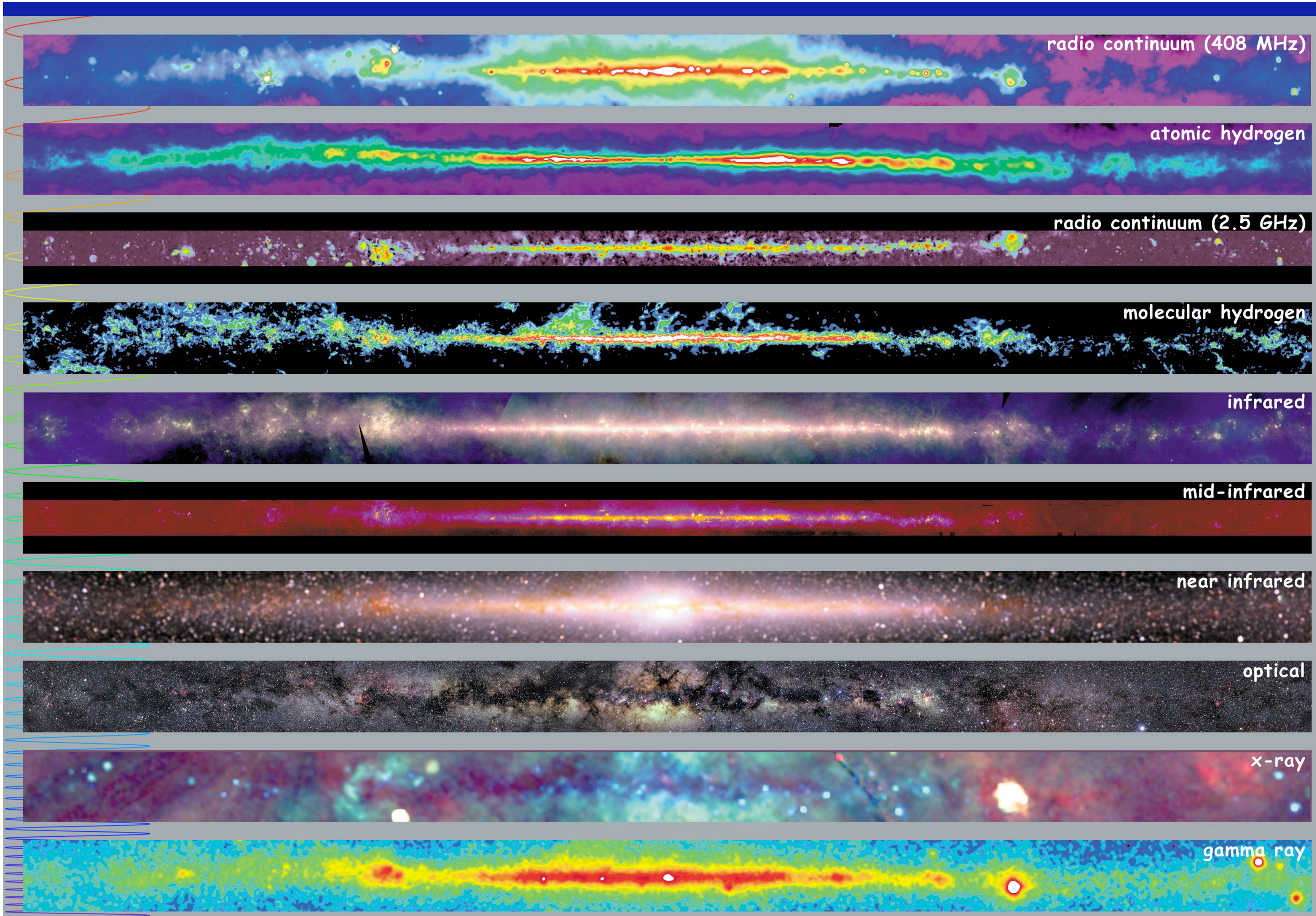


Topics today

- General introduction and blackbody radiation
- The different phases of the ISM, heating and cooling processes
- Radiation from a few selected important molecules
- Masers
- Forbidden lines
- Radiation transport and column density determination

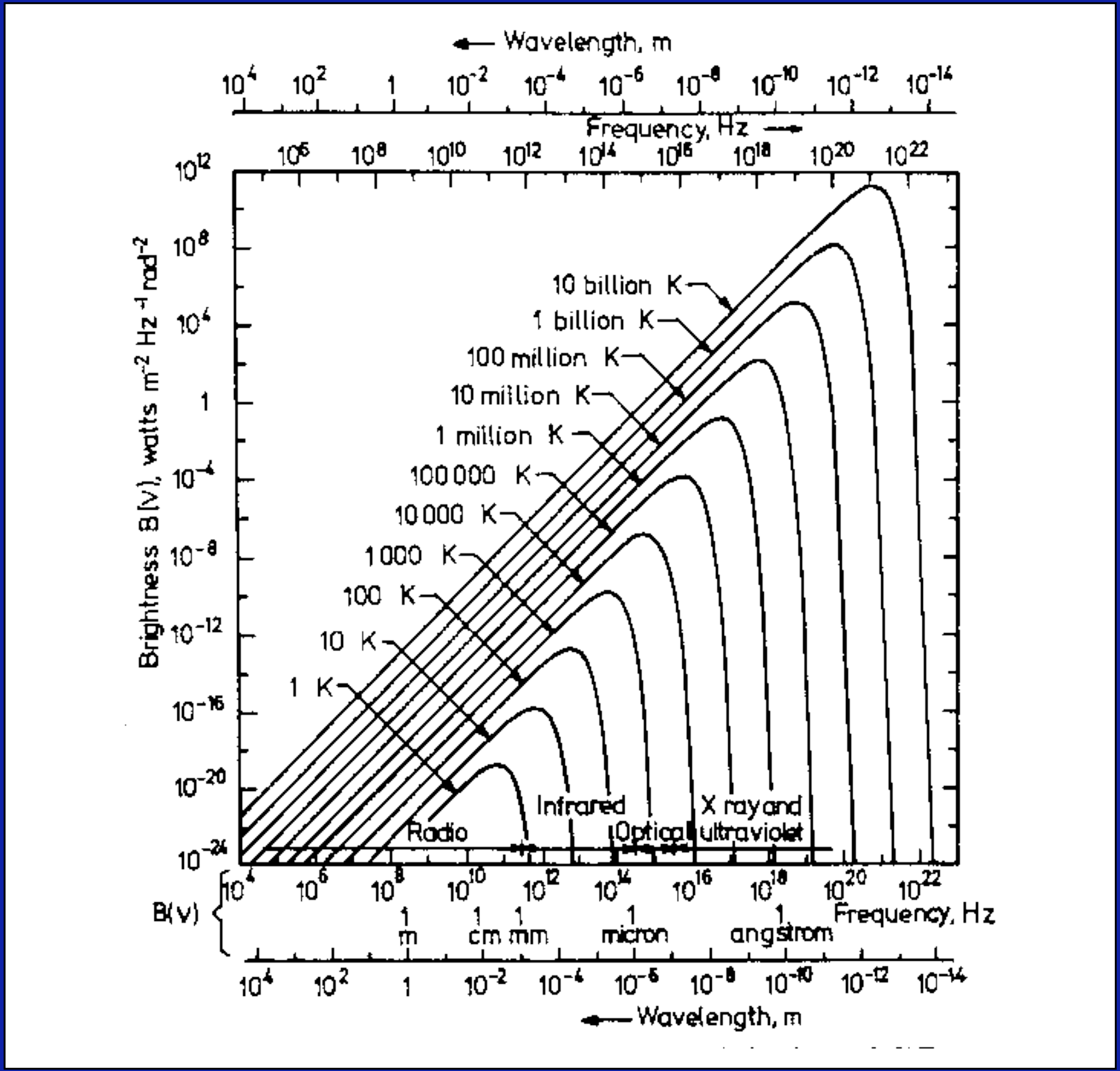


http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

Planck's Black Body

$$B_\nu(T) = \frac{2h\nu}{c^2}\frac{1}{e^{h\nu/kT-1}}$$

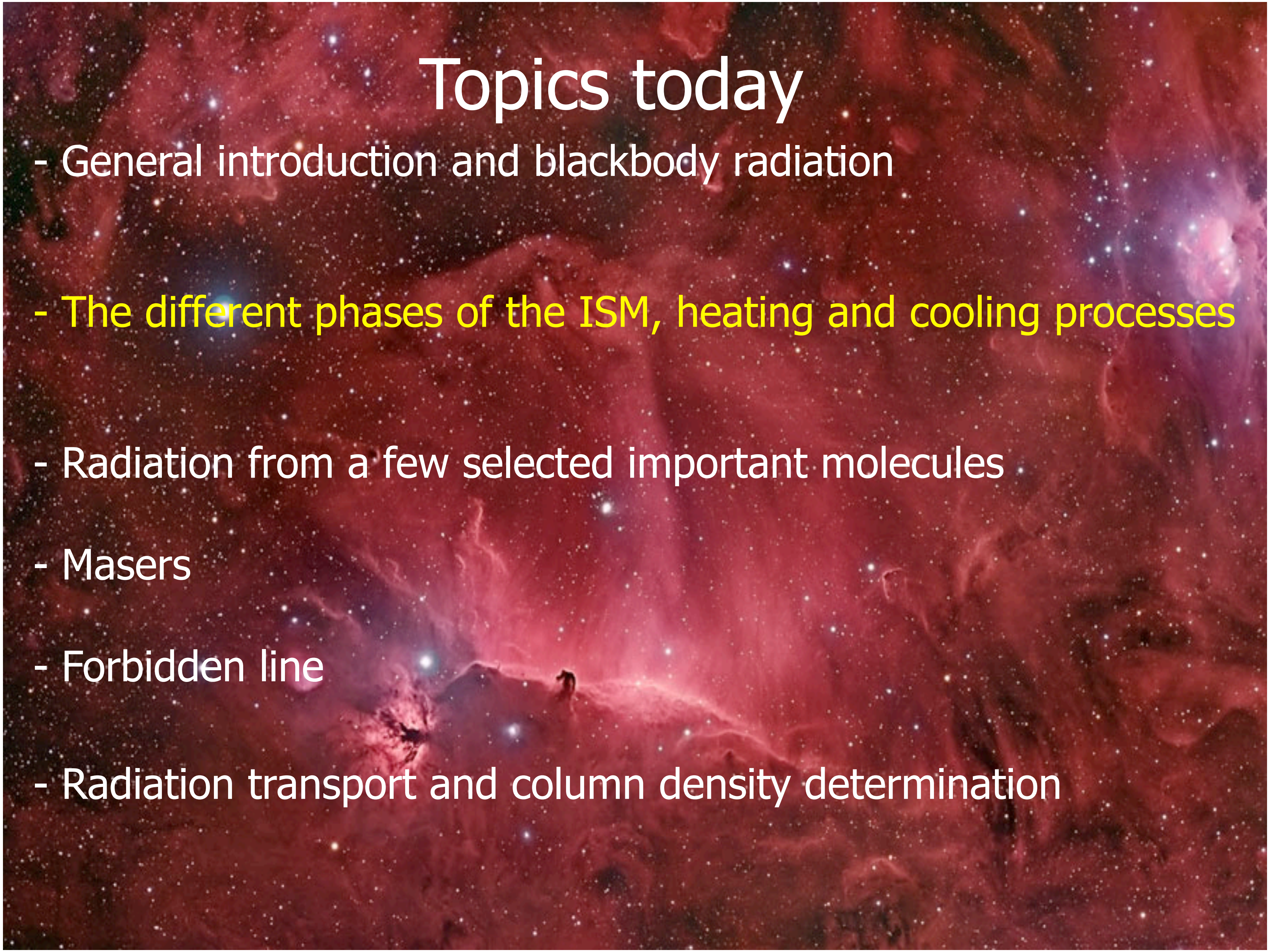


Wien's Law

$$\lambda_{max} = 2.9/T \text{ [mm]}$$

Examples:

The Sun	$T \sim 6000$ K	$\Rightarrow \lambda_{max} = 480$ nm (optical)
Humans	$T \sim 310$ K	$\Rightarrow \lambda_{max} = 9.4$ μm (MIR)
Molecular Clouds	$T \sim 20$ K	$\Rightarrow \lambda_{max} = 145$ μm (FIR/submm)
Cosmic Background	$T \sim 2.7$ K	$\Rightarrow \lambda_{max} = 1.1$ mm (mm)



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The Interstellar Medium I

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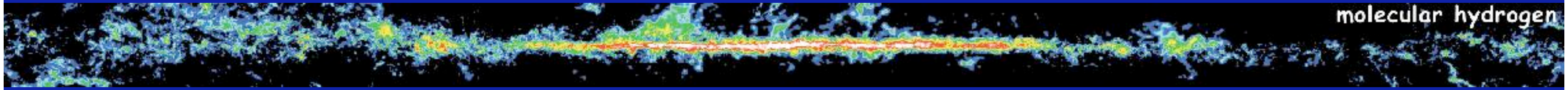
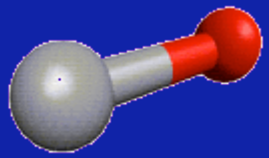
The Interstellar Medium II

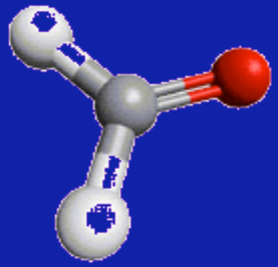
Molecular Component



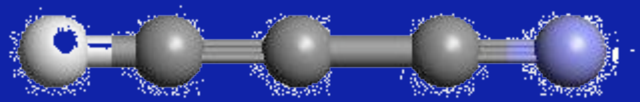
Carbon monoxide CO



Formaldehyde H_2CO



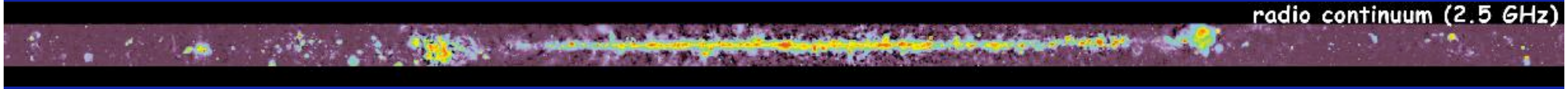
Cyanoacetyline HC_3N



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

The Interstellar Medium III

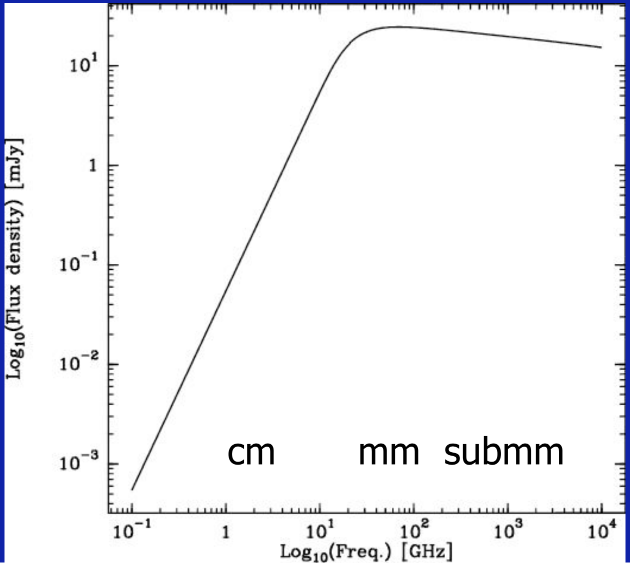
Ionized gas



- H_2 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^+



Heating processes

- Energy injection from outflows/jets
- Energy injection from supernovae
- UV radiation from stars
- Cosmic rays interaction 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: ions also important for ion-molecule chemistry)
- Interstellar radiation (diffuse field permeating interstellar space)

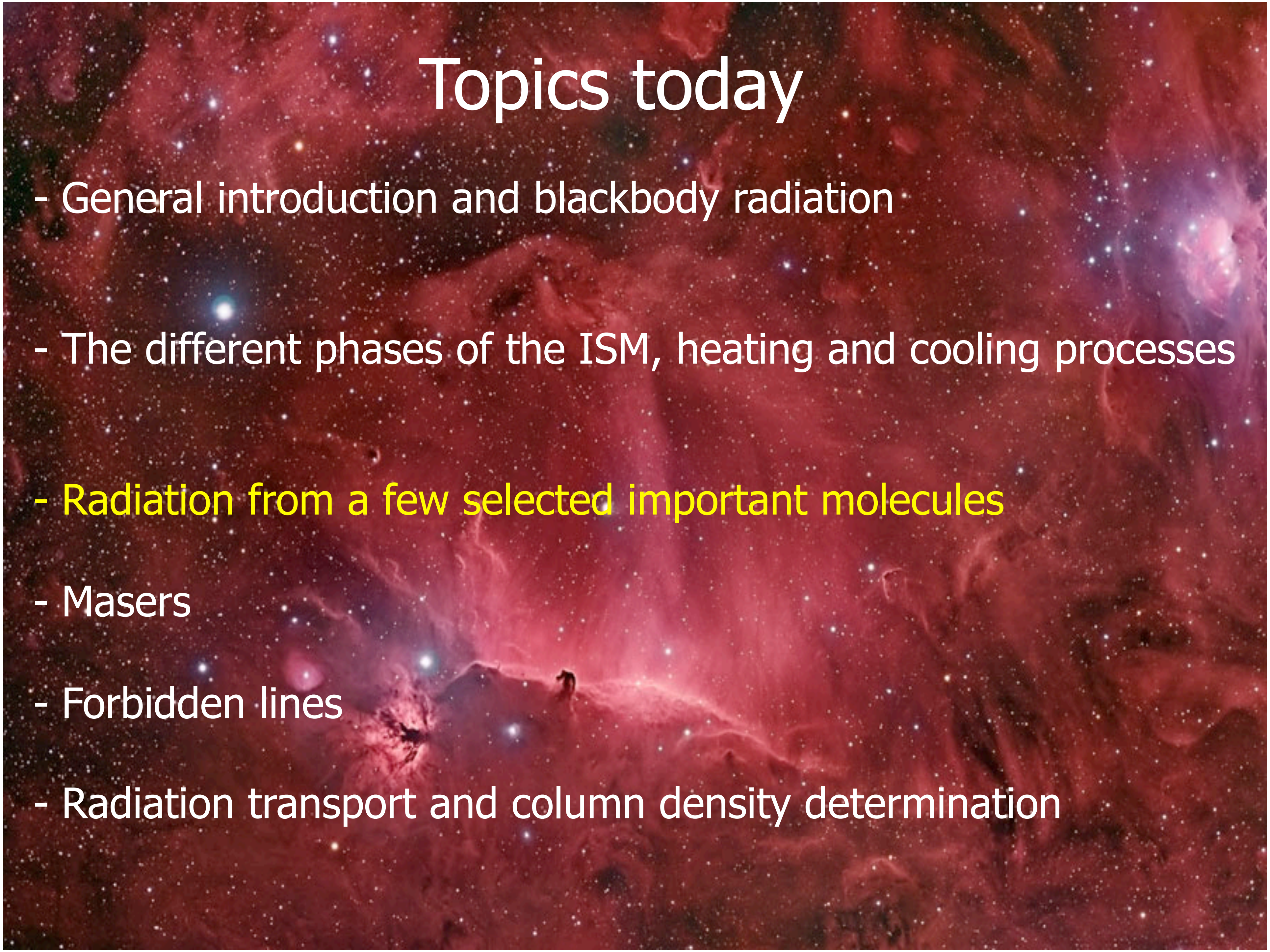
  Mainly dissociates carbon (lower ionization potential than H_2).

  $C + h\nu \dashrightarrow C^+ + e^-$ The electron then disperses energy to surrounding atoms 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

- Major constituents H & H_2 have no dipole moment and hence cannot effectively cool in quiescent molecular cloud. Other coolants required.
  --> Hydrogen collides with ambient atoms/molecules/grains exciting them. The cooling is then done by 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)
  The low-J CO lines are mostly optically thick, the energy diffuses from region to region and escapes from cloud surface. Higher J lines cool directly. CO is 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 (since grains are also heated by radiation gas and dust temperature are usually not equal).



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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											

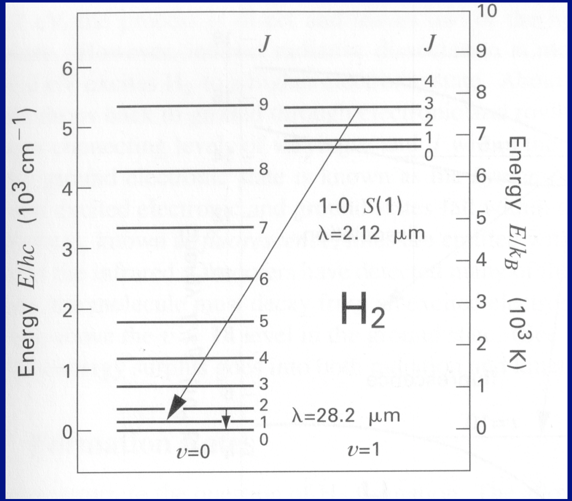
About 160 detected interstellar molecules as of May 2011 (www.cdms.de).
38 (+1 tentative) molecular detection in extragalactic systems.

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

Molecular Hydrogen (H_2)

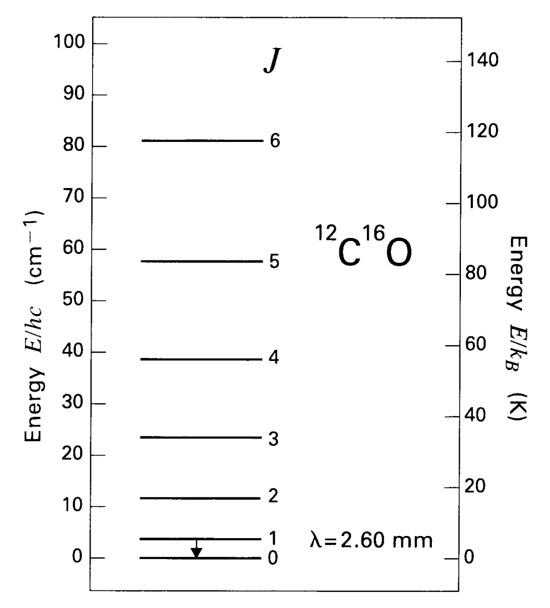
- Since H_2 consists of 2 identical atoms, it has no electric dipol moment and rotationally excited H_2 has to radiate via energetically higher quadrupole transitions with excitation temperatures > 500 K.
  --> cold clouds have to be observed
  other ways, e.g., CO

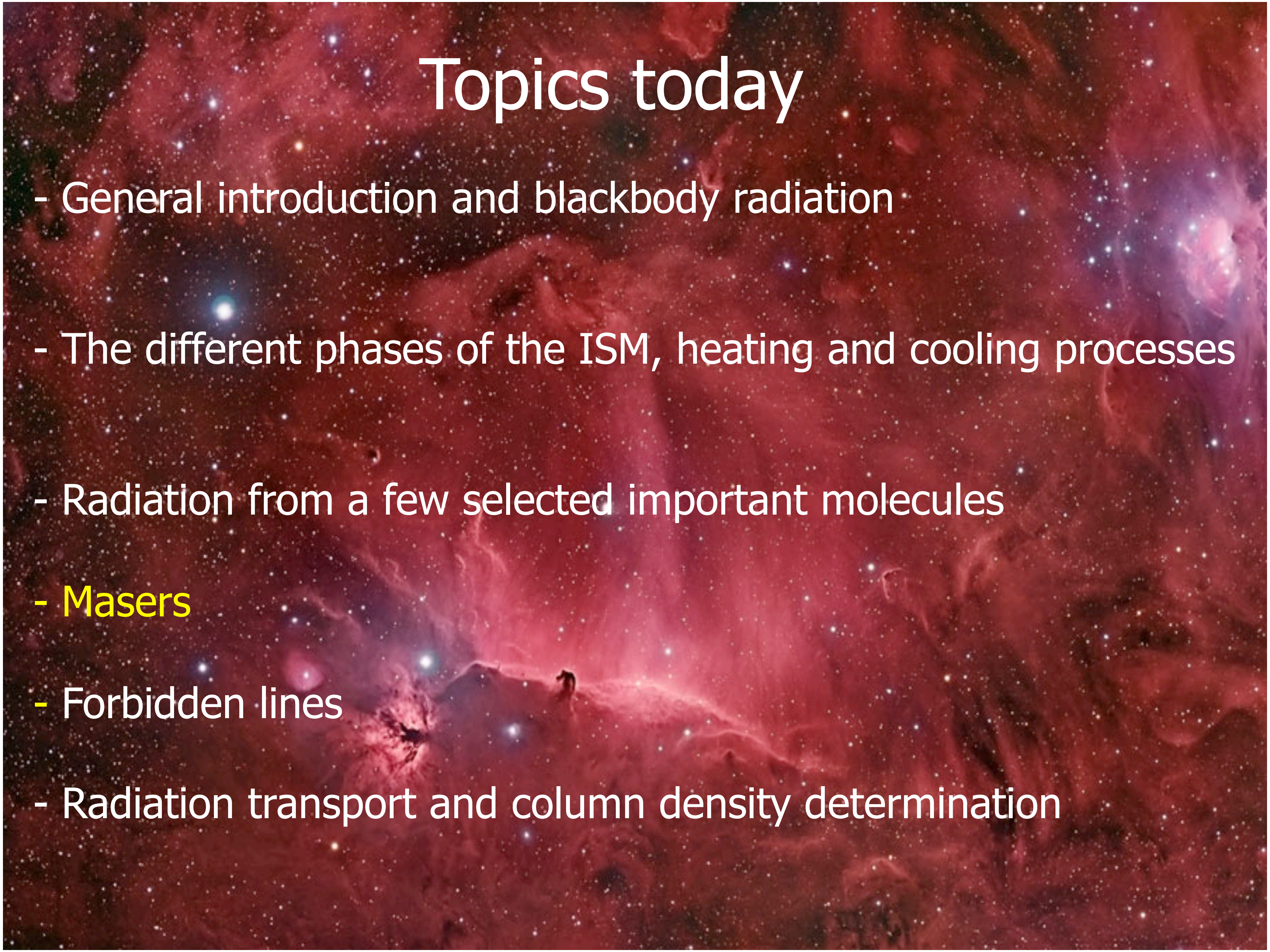


- H_2 can be detected in hot environment.
  Rotational energy:
  Classical mechanics: $E_{rot} = J^2/2I$
  (J: Angular momentum; I: Moment of inertia)
  Quantum-mechanical counterpart: $E_{rot} = h^2/2I \times J(J+1)$
  $= BhI \times J(J+1)$
  (J: rotational quantum number; B: rotational constant)
- Small moment of inertia --> large spread of energy levels
  Allowed quadrupole transitions $\Delta J = 2$
  --> lowest rotational transition J=2-0 has energy change of 510 K

Carbon monxide (CO)

- Forms through gas phase reactions similar to H_2.
- Strong binding energy of 11.1 eV helps to prevent much further destruction (self-shielding).
- Has 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 $n_{crit} = A/\gamma \sim 3 \times 10^3 \mathrm{cm}^{-3}$.
  (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 $g_J = 2J + 1$)
  The excitation temperature T_{ex} is a measure for the level populations and equals the kinetic temperature T_{kin} if the densities are > n_{crit}.





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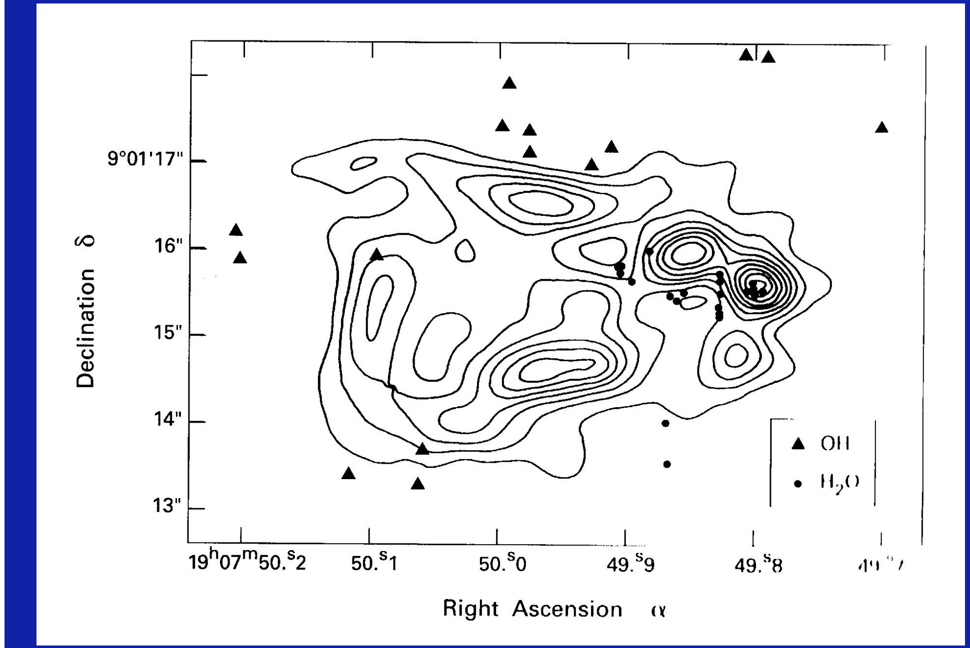
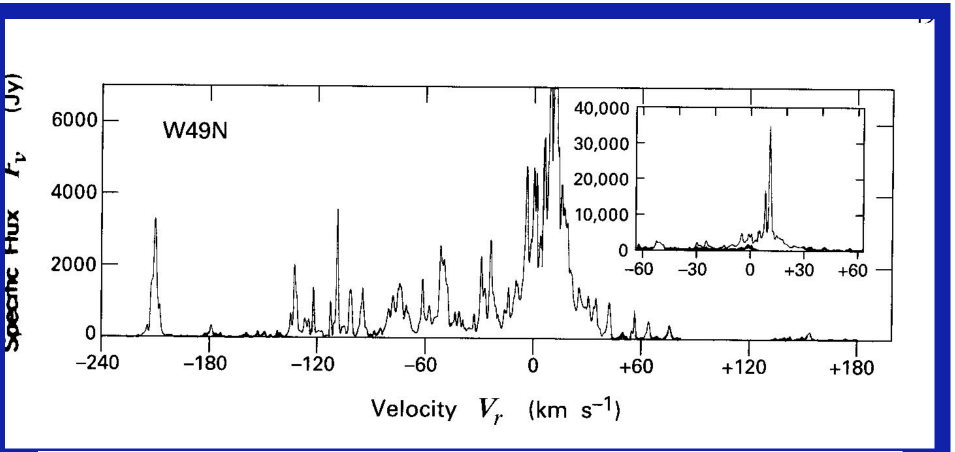
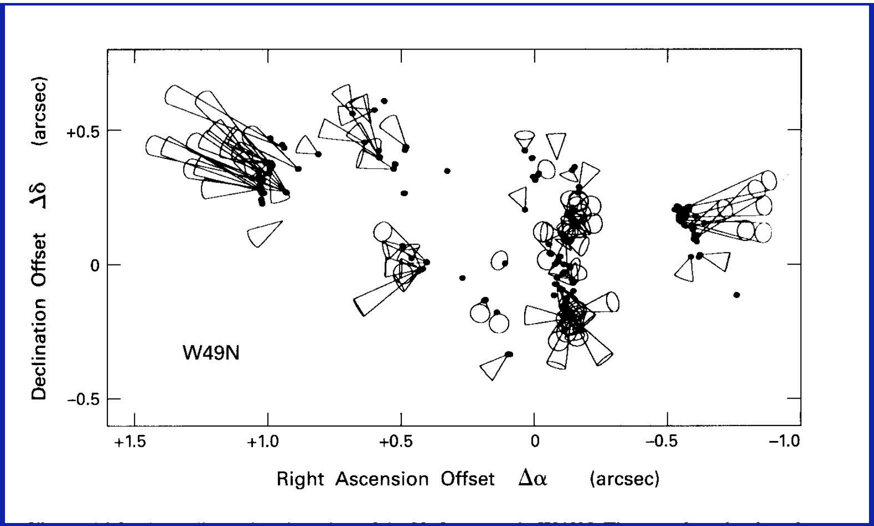
Molecular Masers I



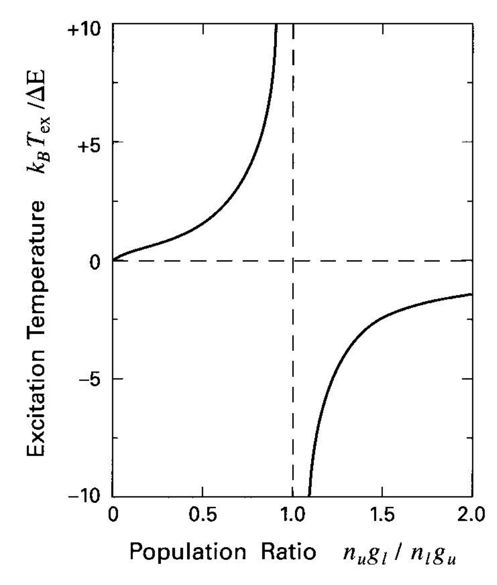




- In the Rayleigh-Jeans limit, brightness temperature T and intensity I relate like $T = c^2/2k\nu^2 I$ with $I=F/\Omega$ (Ω: solid angle). With the small spot diameters (of the order some AU), this implies brightness temperatures as high as 10^{15}K, far in excess of any thermal temperature --> no thermal equilibrium and no Boltzmann distribution.
- Narrow line-width
- Potential broad velocity distribution.
- They allow to study proper motions.

Molecular Masers II

- The excitation temperature is defined as: $n_u/n_l = g_u/g_l \exp(-h\nu/kT_{ex})$.
- For maser activity, population inversion is required, i.e., $n_u/g_u > n_l/g_l$.
  --> This implies negative excitation temperatures for maser activity.
- In thermal conditions at a few 100K, for typical microwave lines
  $E_{line} = h\nu/k < T_{kin} \sim T_{ex}$ --> $n_u/g_u \sim n_l/g_l$
  --> Only a relatively small shift is required in get population inversion

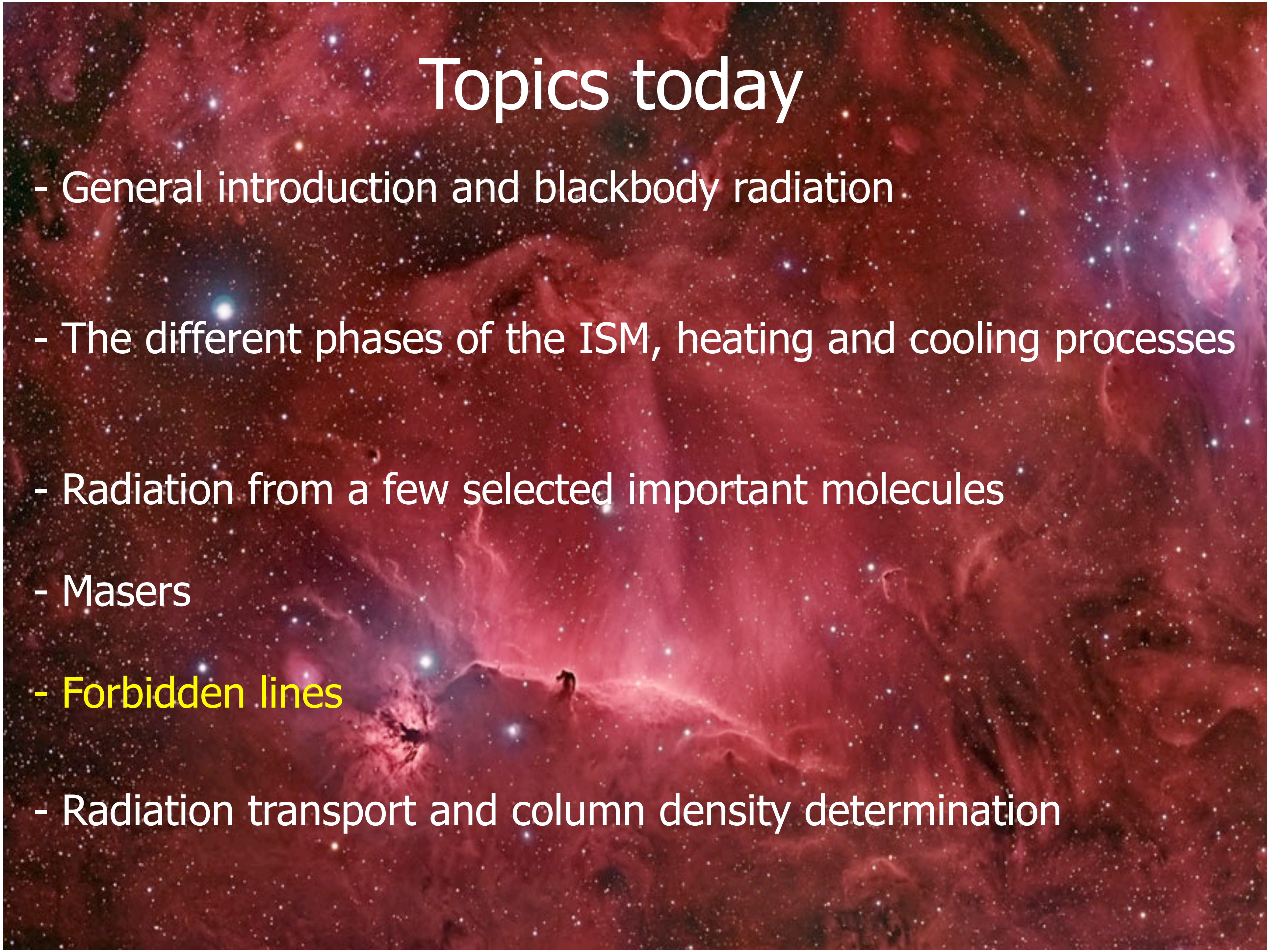


$T_{ex}/E_{line} = -1/\ln(n_u g_l/n_l g_u)$

With rising T_{ex} the level populations are approaching each other, and then one has only to “overcome the border”.

Different proposed pumping mechanisms, e.g.:
- Collisional pumping in J- and C-shocks of protostellar jets for H_2O masers.
- Radiative pumping at shock fronts between UCHII regions and ambient clouds.

In both cases, very high densities and temperatures are required.



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Forbidden lines I

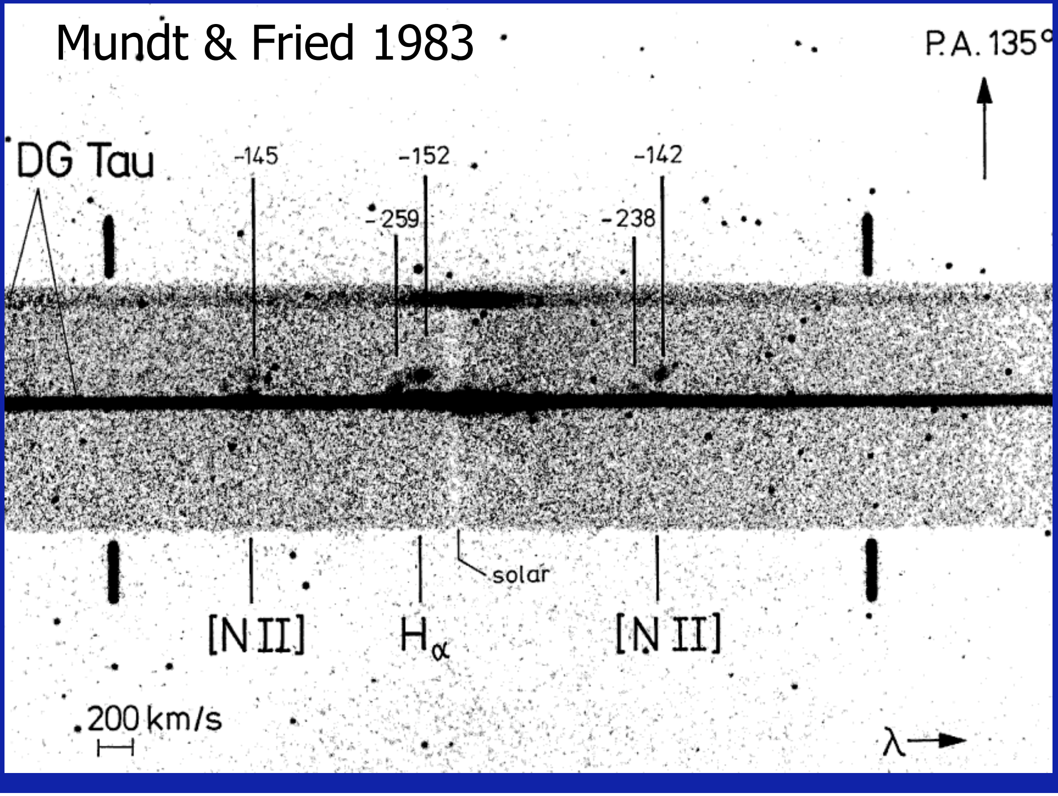
Protostellar jets discovered in optical forbidden emission lines

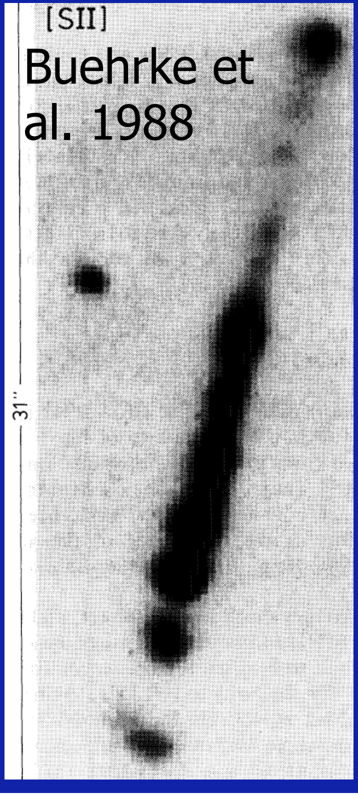
Examples: DG Tau (Mundt & Fried 1983), HH34 (Bührke et al. 1988)

Associated to / interrelated with **HH objects:**

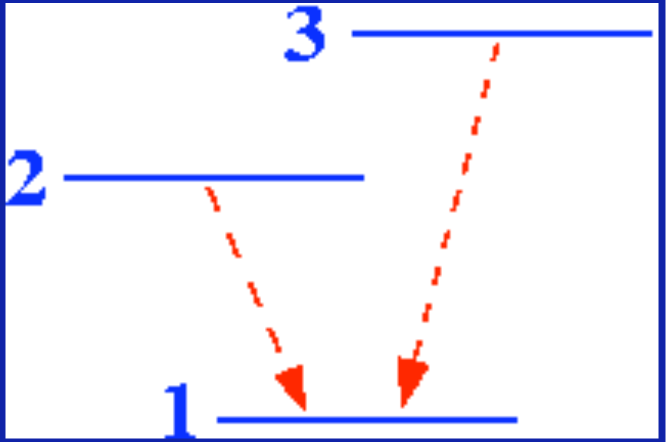
= nebulous (narrow) emission line regions (Herbig and Haro in the 40ies), see online catalogue by Bo Reipurth, http://casa.colorado.edu /hhcat/)

= shock-excited emission in dilute gas (Schwartz 1975, Raymond 1979)


Mundt & Fried 1983


Buehrke et al. 1988

Forbidden lines II



Why forbidden?

- radiative transition to certain atomic energy state “not allowed” (probability is very very low) by selection rules
- In lab collisional de-excitation, only at low densities in space possible

- (electric) dipole selection rules for many electron atom:

DS = 0 (spin)
DL = 0, +1, -1 (orbital angular momentum)
DJ = 0, +1, -1   (total angular momentum)
Dm= 0, +1, -1   polarized light (magnetic quantum number m)

- higher order transitions if electric dipole transition “forbidden”:

2nd order electric dipole, magnetic dipole

- transition rates / radiative life times

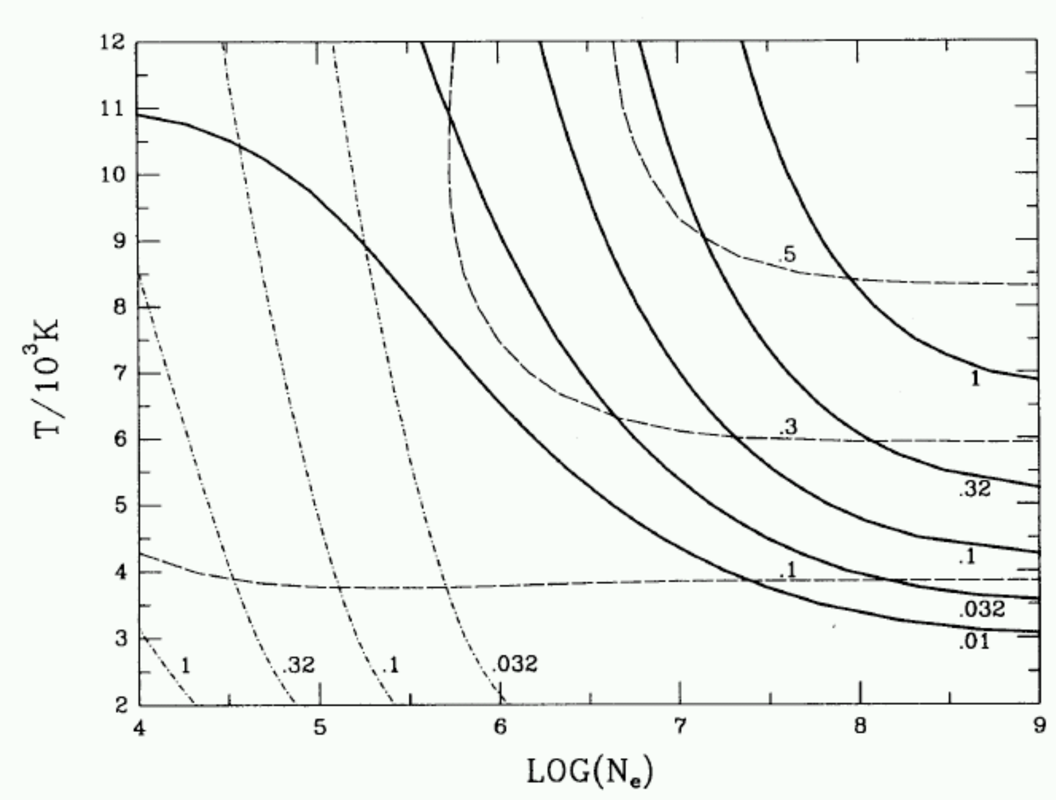
E1:   10e8 .. 10e9 /s - 1- 10 ns
E2 / M1:   10e3 .. 10e6 /s - 1ms - 1s

-> transition rates of higher order transtions much lower, life times much larger

Forbidden lines III

FEL intensity ratio as tracer for temperature & density

e.g. [OI] 557.7nm (solid), [SII] 673.1nm (dash-dotted) & [SII] (406.9+407.6nm) (dashed) as function of electron density Ne & temperature T, all optically thin (Kwan & Tademaru 95)



- strength of [SII] (406.9+407.6nm) to constrain T for [OI] 557.7nm emission regions
- for Ne > 10e6:
  [SII] 407.6/406.9 ~0.22 ~const.
  -> [SII] (406.9+407.6) have critical densities for collisional de-excitation
- comparion to observations:
  [OI] 557.7/630.0 ~ 0.1 ... 1.0 for low velocity component of wind/jet
  -> lower limit on Ne = 3x10^6 /cm^3 at T = 10^4 K
  to Ne = 2x10^8 /cm^3 at T = 4.5x10^3 K

Summary

- Different wavelengths trace different physical processes and temperatures.

- For example, atomic component via HI spin-flip transitions, molecular component via rotational, vibrational and electronic transitions and ionized via recombination lines or free-free emission.

- Discussed several different heating and cooling mechanisms.

- Radiation of selected molecules.

- Maser and forbidden line emission.

- Basic radiation transfer, column density determination and CO → H_2 conv..

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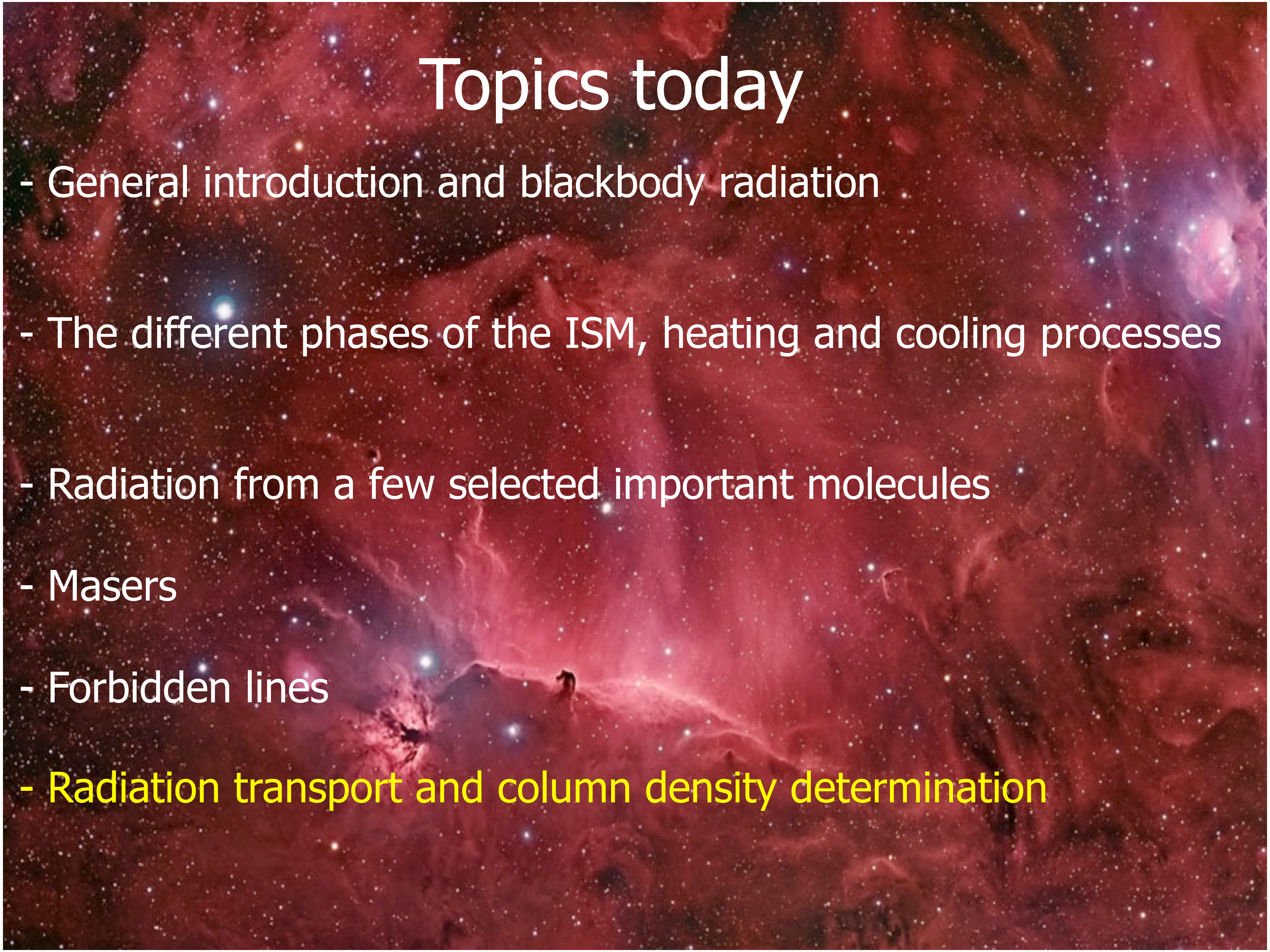

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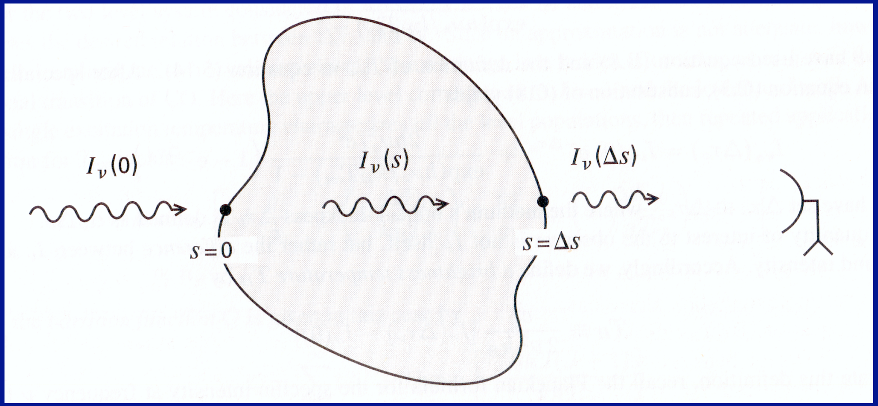
Radiation transfer I



$$dI_\nu = -\kappa_\nu I_\nu ds + \varepsilon_\nu ds$$

with the opacity

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

and the source function

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

$$\Rightarrow dI_\nu / d\tau_\nu = I_\nu - S_\nu$$

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

$$g_J = 2J + 1$$

In thermal equilibrium

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

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

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

And 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

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

Subtracting further the background radiation

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

Molecular column densities

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

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

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 ∫ T dv.

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

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

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

$$Q = kT/hB.$$

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

Conversion from CO to H_2 column densities

One classical way to derive conversion factors from CO to H_2 column densities and gas masses essentially relies on three steps:

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

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

- 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, the CO observations can directly be converted to H_2 column densities. Assumptions about the 3D cloud geometry allow further estimates about the cloud masses and average densities.