Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

15.10 Today: Introduction & Overview (Beuther)
22.10 Physical processes I (Beuther)
29.10 --
05.11 Physcial processes II (Beuther)
12.11 Molecular clouds as birth places of stars (Beuther)
19.11 Molecular clouds (cont.), Jeans Analysis (Henning)
26.11 Collapse models I (Beuther)
03.12 Collapse models II (Beuther)
10.12 Protostellar evolution (Gieser)
17.12 Pre-main sequence evolution & outflows/jets (Henning)
07.01 Accretion disks I (Henning)
14.01 Accretion disks II (Henning)
21.01 High-mass star formation, clusters and the IMF (Gieser)
28.01 Extragalactic star formation (Henning)
04.02 Planetarium@HdA, outlook, questions
11.02 Examination week, no star formation lecture (Beuther, Gieser, Henning)

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

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html

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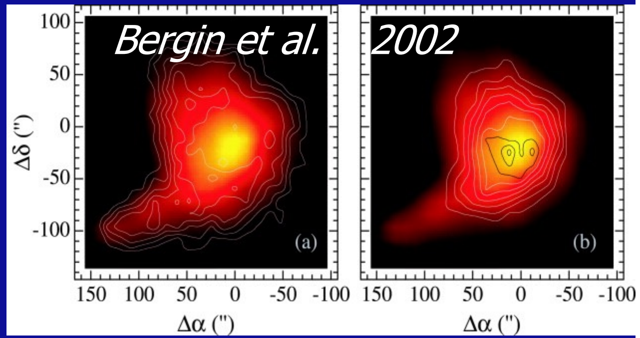
Last Week

- Main tools: Spectral line emission, and thermal emission and extinction from dust.

- Molecules interesting for themselves and chemistry.

- However, also extremely useful to trace physical processes.

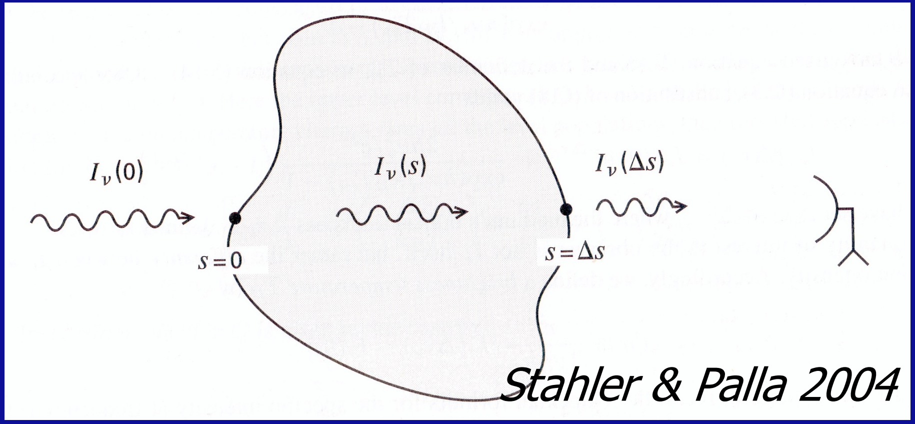
- Molecules deplete on grains at low temperatures.



- Discussed main cooling and heating processes.

- Discussed basic line radiation transfer and column density determination.

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

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

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

$$N_u = 3k/8\pi^3\nu \ \ 1/\mu^2 \ (2J_u-1)/J_u \ \ \tau /(1 - e^{-\tau}) \ \ (T\Delta\nu \ sqrt(\pi)/(2sqrt(ln2))$$

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-V} and optical extinction A_v

   $A_v = 3.1\ E_{B-V}$ (Savage and Mathis, 1979)

2) The ratio $N(H_2)/E_{B-V}$: 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.

Topics today

- Line profiles and a few applications for line emission

- Magnetic field measurements (Zeeman and dust)

- Maser emission

- Dust properties

- Physical distributions (Maxwell, Planck, Boltzmann, Saha)

Line broadening

- Natural line broadening: Disturbance of molecule by zero-point vibrations of electromagnetic field

$$d\nu = 32\pi^3\nu^3 \mu^2/(3hc^3)$$ (μ: Dipole moment)

For CO(1-0) → $d\nu \sim 3.5\times10^{-8}$ Hz or $dv \sim 9\times10^{-14}$ km/s → Negligable!

- Pressure broadening: Arises from collisions between molecules. Quantum-mechanical problem of intermolecular forces.
  → At densities of star-forming regions negligable.

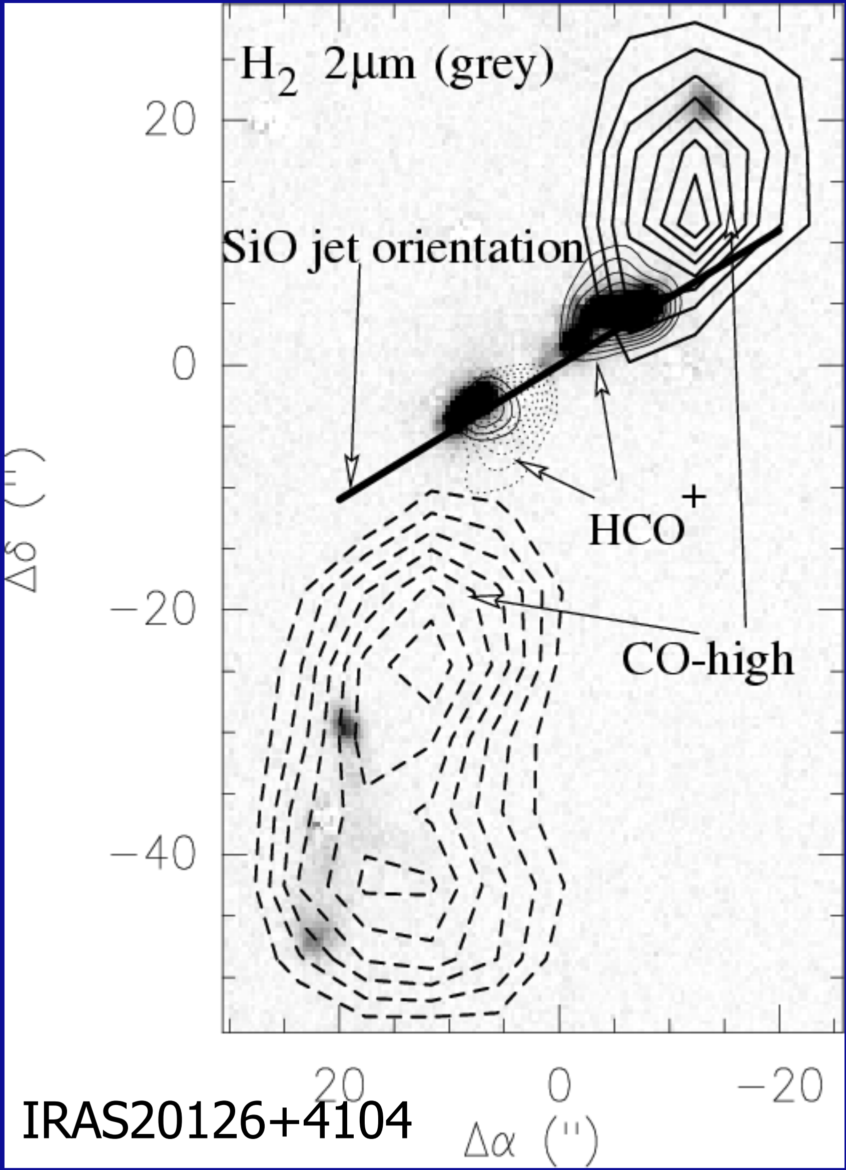
- Thermal line broadening: Thermal motions of gas cause doppler broadening:

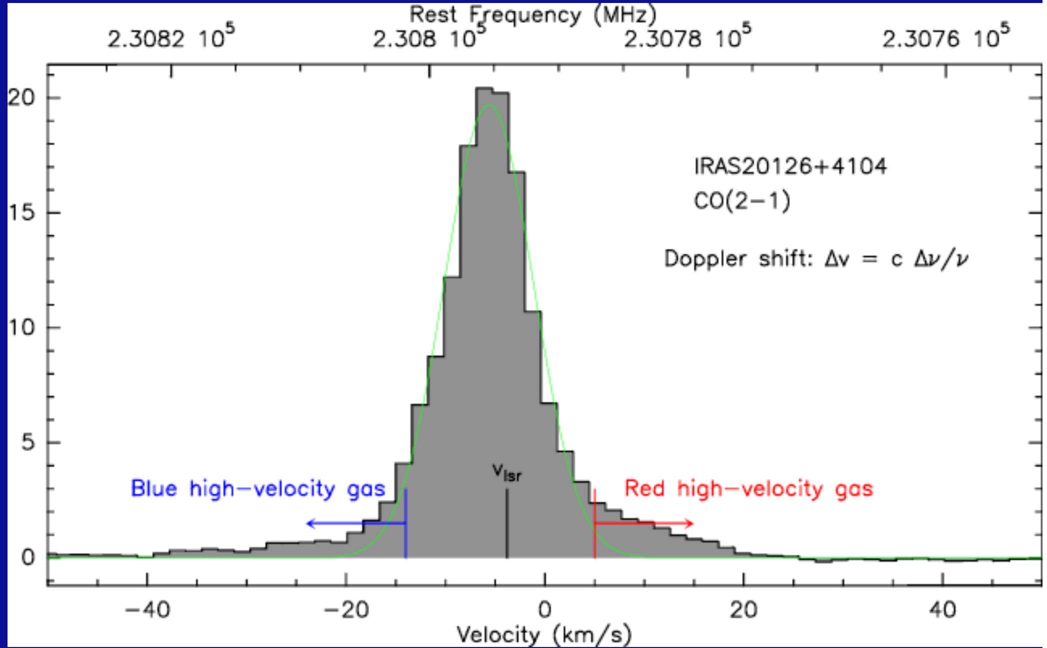
$$dv = \sqrt{(8\ln 2\, kT/m_{mol})}$$

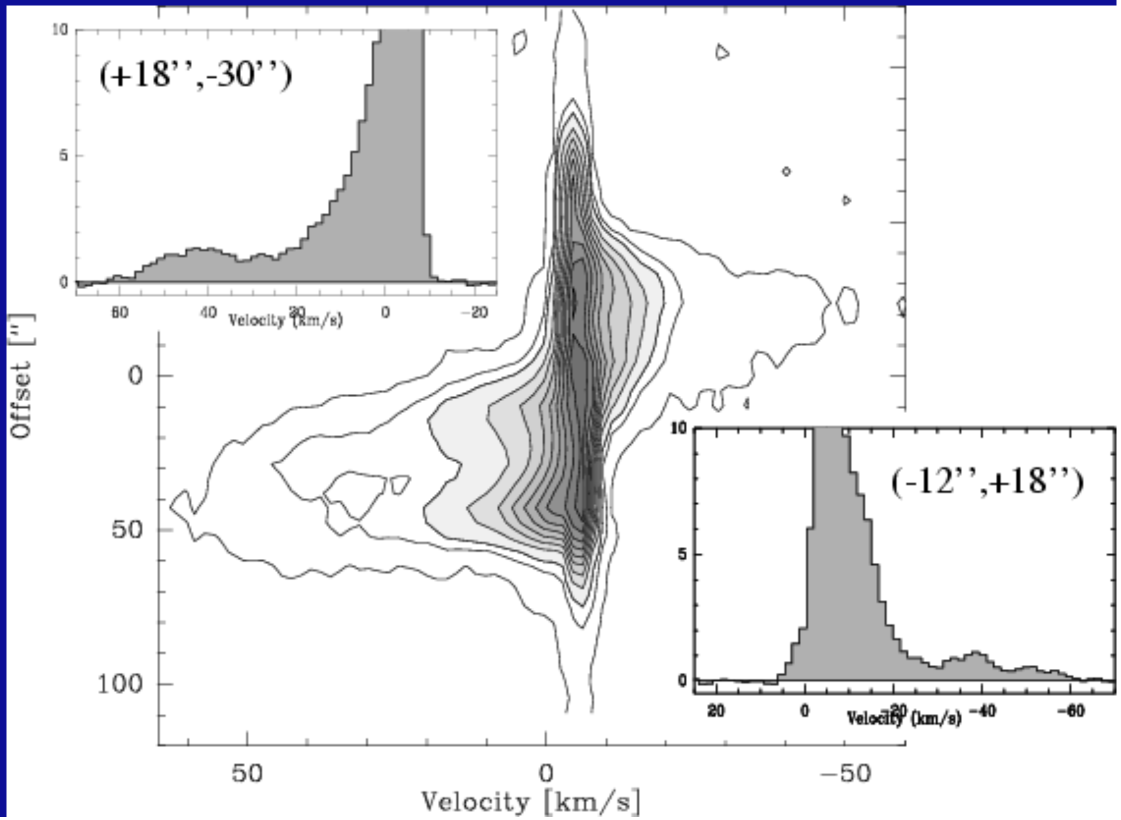
→ $dv(NH_3@30K) \sim 0.28$ km/s

→ Other physical effects: Line broadening due to outflow motions, rotation …

Molecular outflows







Lebron et al. 2006

Molecular gas structure of the Galaxy based on CO observations

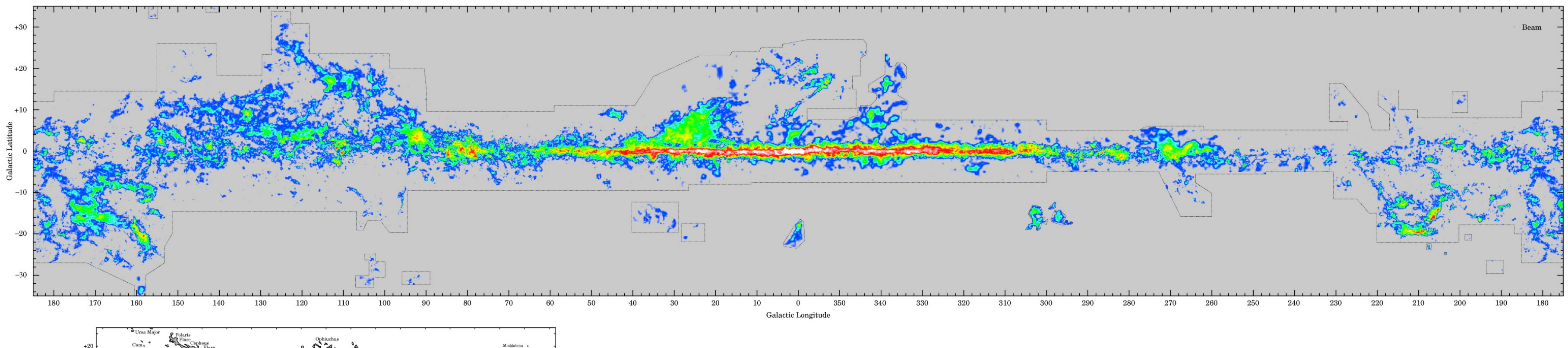


Fig. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

Dame et al. 2001

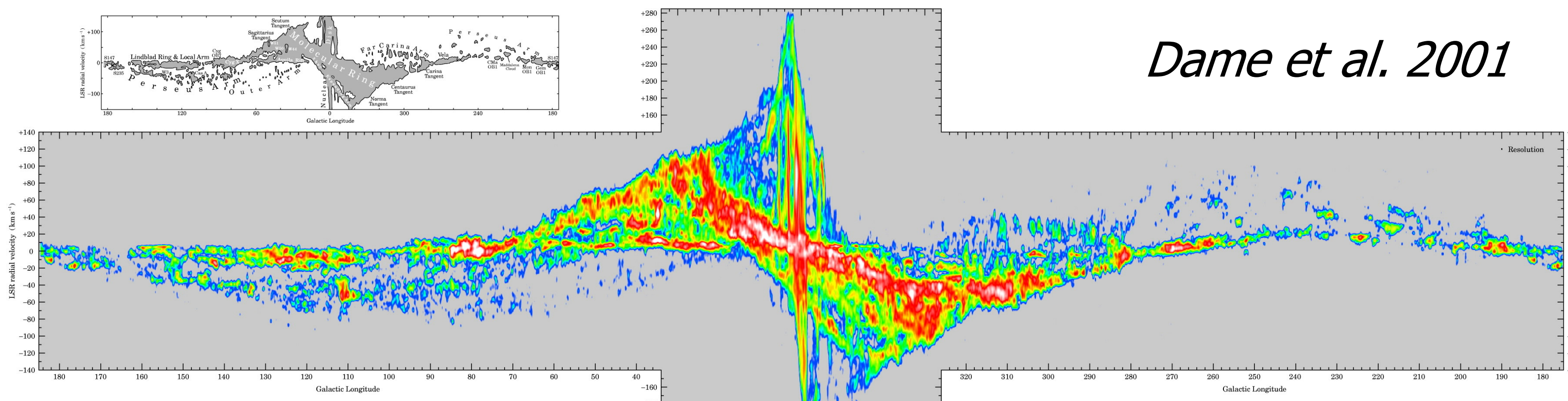
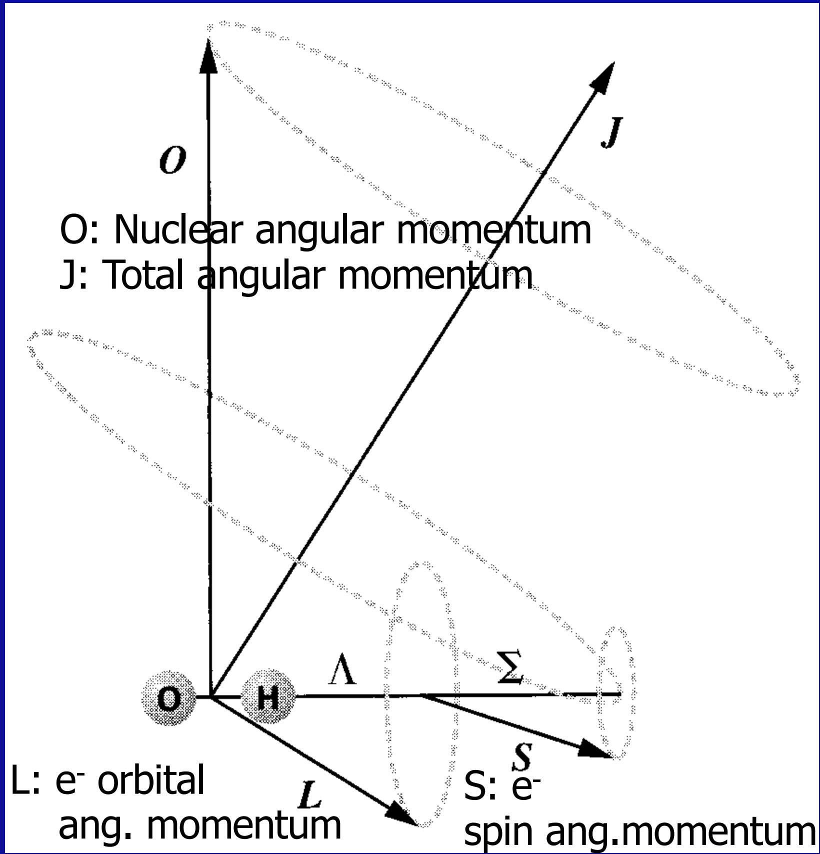


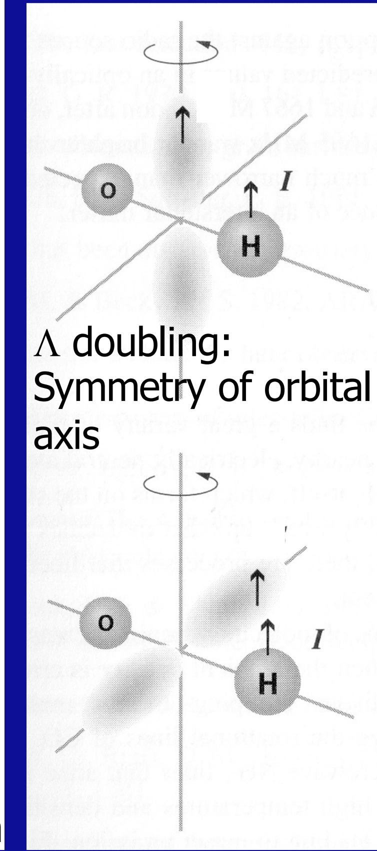
Fig. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-σ level (see §2.2).

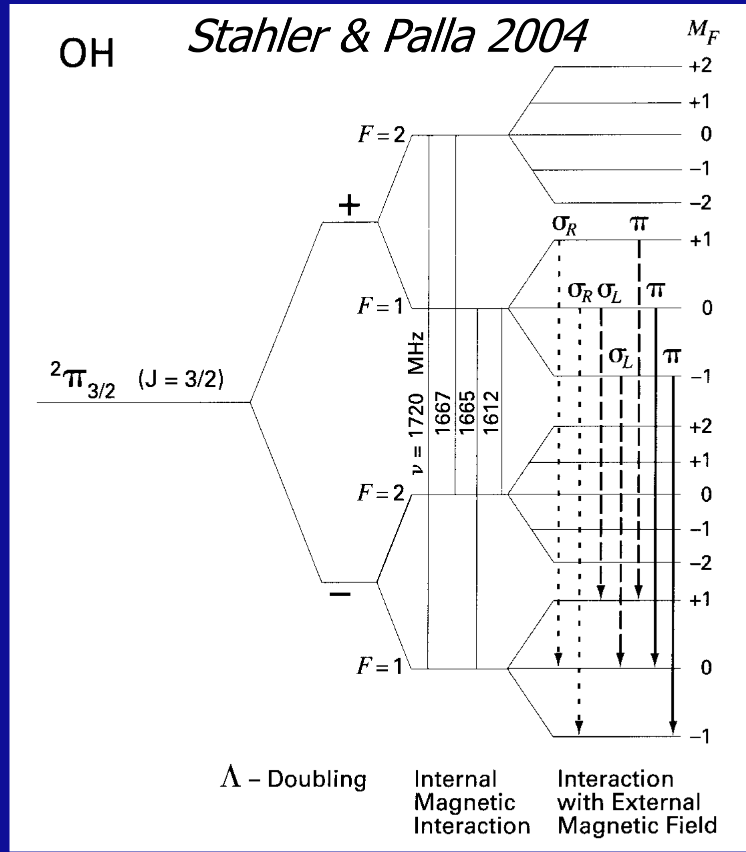
Topics today

- Line profiles and a few applications for line emission
- Magnetic field measurements (Zeeman and dust)
- Maser emission
- Dust properties
- Physical distributions (Maxwell, Planck, Boltzmann, Saha)

The Zeeman effect and magnetic fields I



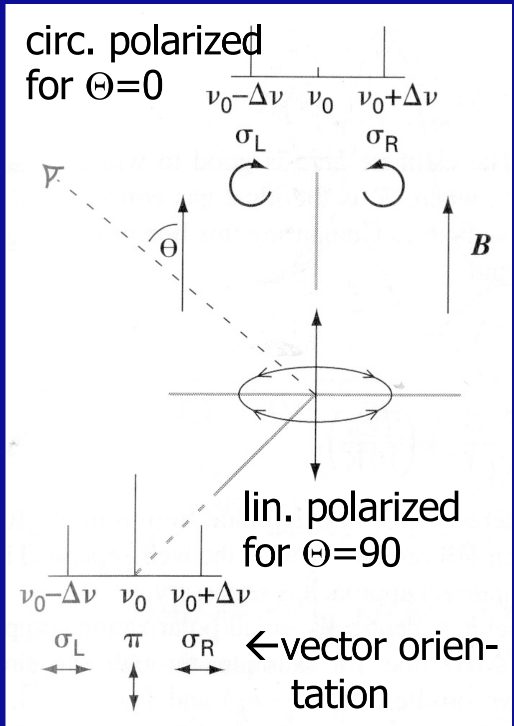


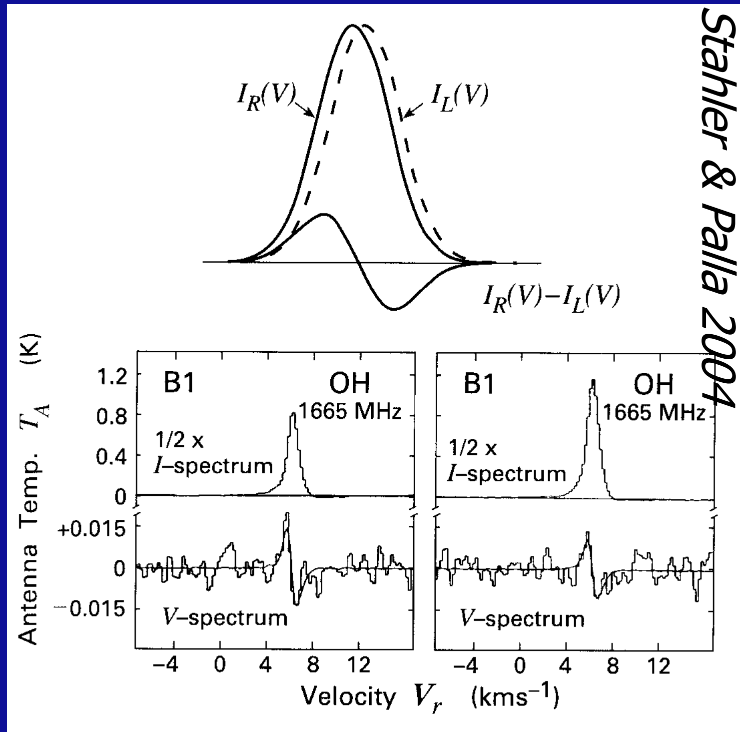


- OH free radical with unpaired free e^- and hence non-zero electronic angular momentum. Highly reactive in lab, but can survive in space.
- Λ doubling → symmetry difference of the e^- orbital to rotation axis
  → energy splitting.
- Interaction between spins of e^- and H nucleus → magn. hyperfine splitting.

External magnetic field → produces Zeeman splitting.

The Zeeman effect and magnetic fields II





$\Delta\nu_{mag} \sim B$ usually of the order a few 10 μG

←Subtraction of left- from right-handed circ. pol. results in Stokes-V spec.

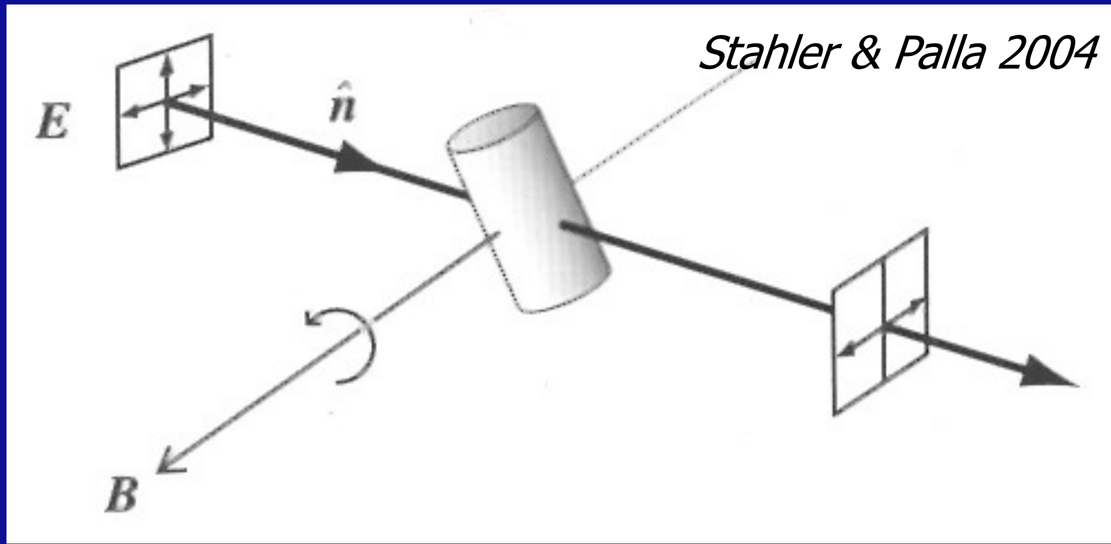
- Zeeman splitting of $\Delta\nu_{mag} = (b/2)\,B$ (b: constant, B: Magnetic field)

- Orientation between **B** and line of sight causes different polarization properties
  → Θ=0 (l.o.s) circular pol., Θ=90 lin. pol., in reality elliptical polarization.

- Thermal line broadening complicates matter: $\Delta\nu_{mag}/\Delta\nu_{therm} \sim 10^{-3} B(\mu G)$

  → One measures two polarizations differentially.
  → Only sensitive to the B component along the line of sight.

IR dust polarization & dichroic extinction



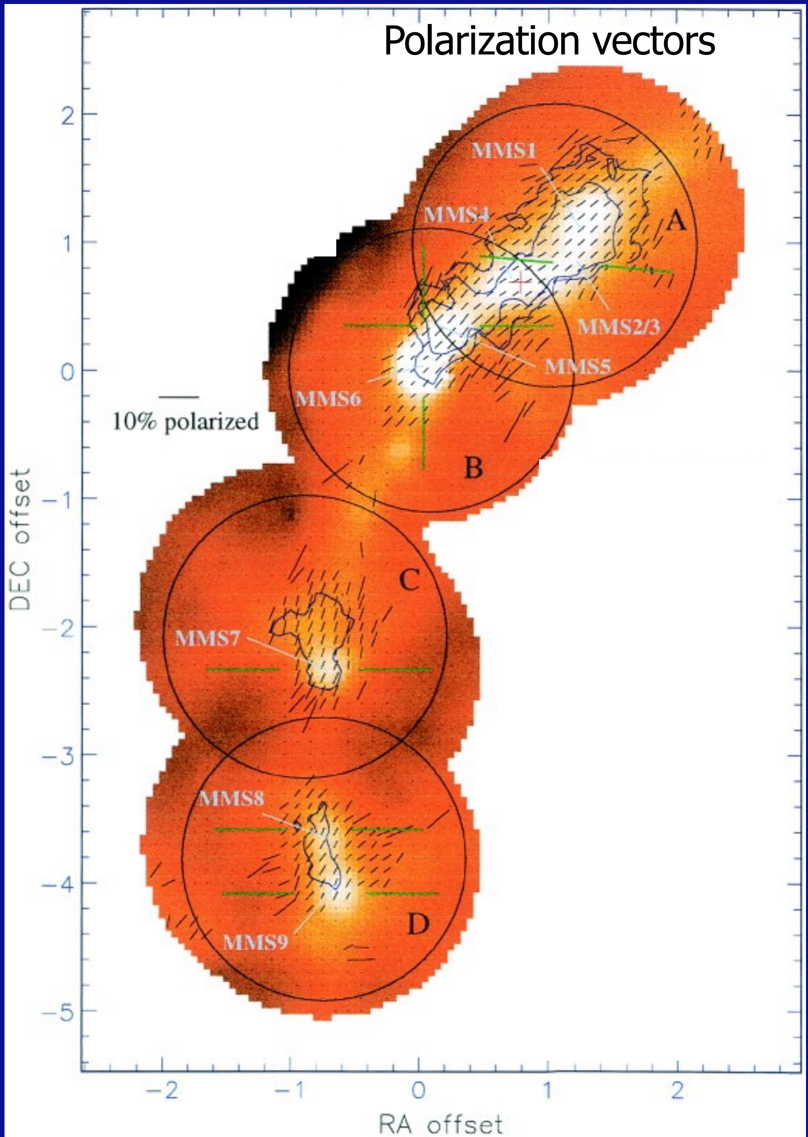
- Incident radiation unpolarized.

- Grains no spheres → small electric charge and paramagnetic
  → rotate about short axis, and magn. moment **M** points along rotation axis.

- External **B** field creates torque **D**=**M**x**B** → grain's short axis aligns with **B**.

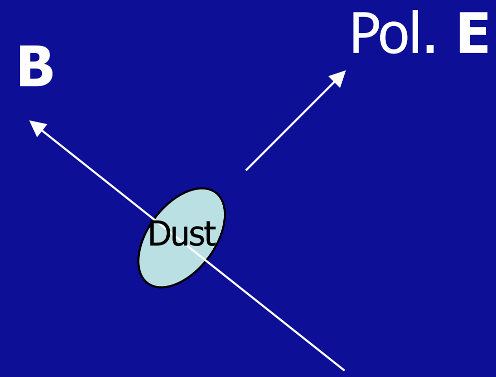
- Absorption best along major axis
  → Polarization afterwards largely along axis of magn. field.

Dust polarization and magnetic fields



Polarized submm continuum emission

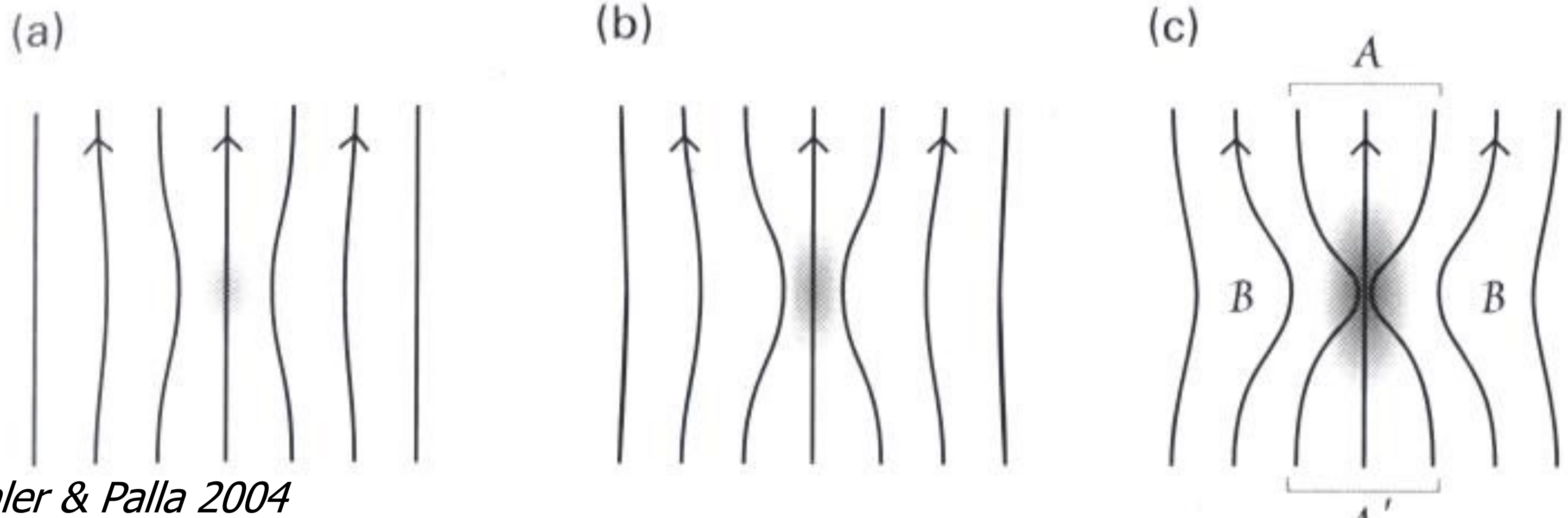
In contrast, thermal dust emission at (sub)mm wavelengths perpendicular to magnetic field!



Molecular filaments can collapse along their magnetic field lines.

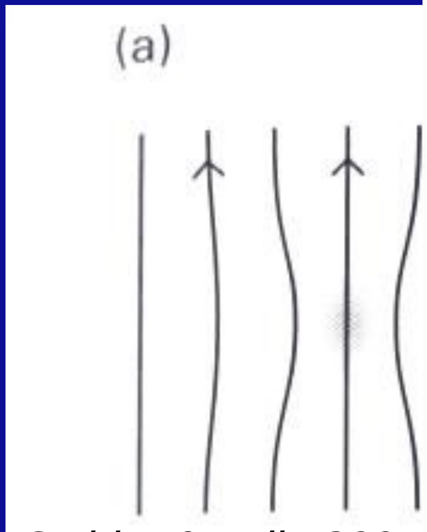
Matthews & Wilson 2000

Ambipolar diffusion

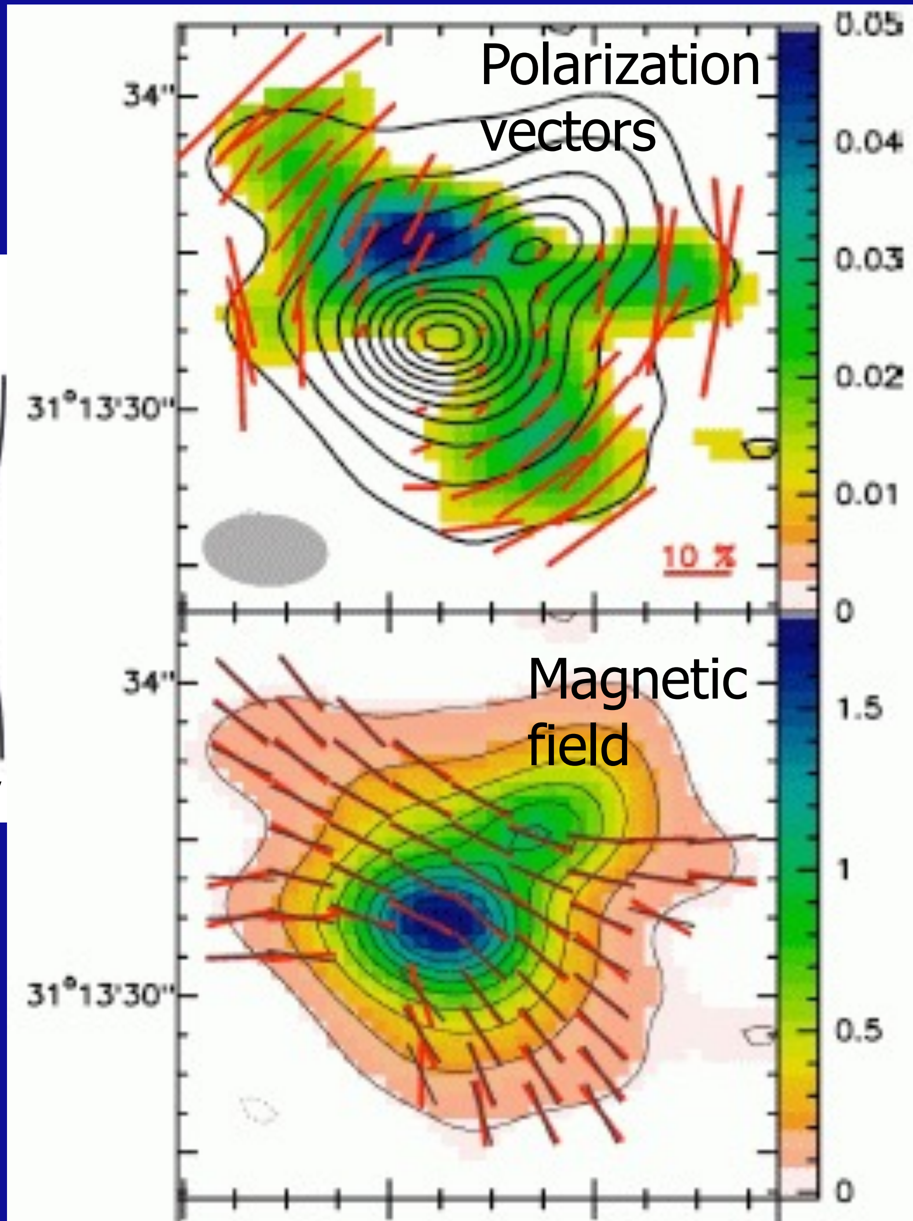


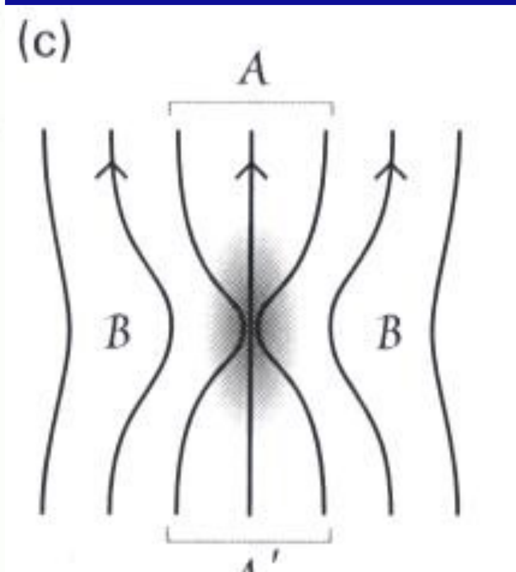
Stahler & Palla 2004

Ambipolar diffusion



Stahler & Palla 2004





B_{pos} ~ 5mG

Girart et al. 2006

Topics today

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- Magnetic field measurements (Zeeman and dust)

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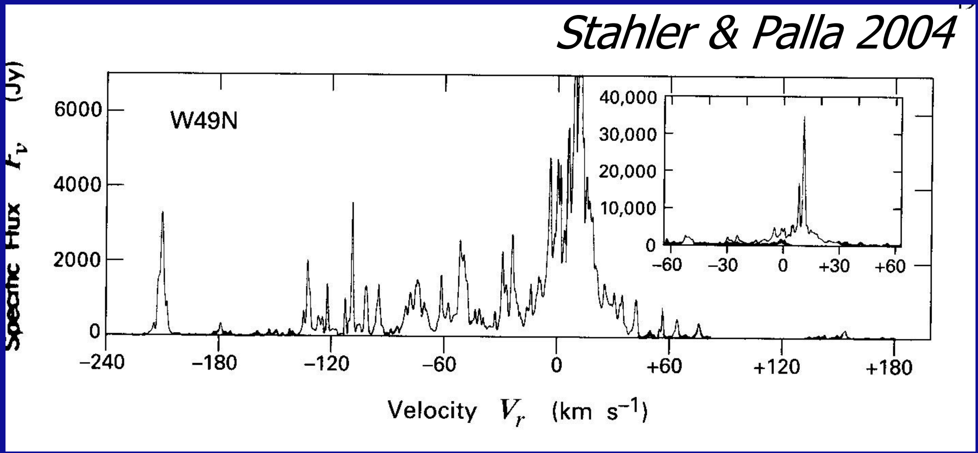
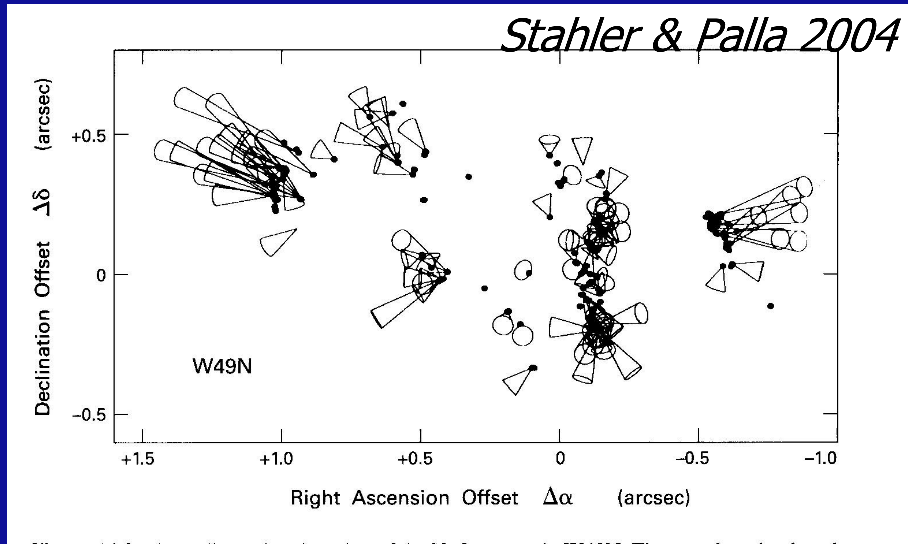
- Dust properties

- Physical distributions (Maxwell, Planck, Boltzmann, Saha)

Molecular Masers I





- Rayleigh-Jeans limit: $T = c^2/2k\nu^2 I$ with $I=F/\Omega$ (Ω: solid angle).

- Small spot diameters (~ some AU) → T as high as 10^{15}K
  → no thermal equilibrium and no Boltzmann distribution.

- Narrow line-width with potential broad velocity distribution (many components).

- They allow to study proper motions.

Molecular Masers II

- Excitation temperature for Boltzmann: $n_u/n_l = g_u/g_l \exp(-h\nu/kT_{ex})$.
- Maser activity requires population inversion: $n_u/g_u > n_l/g_l$.

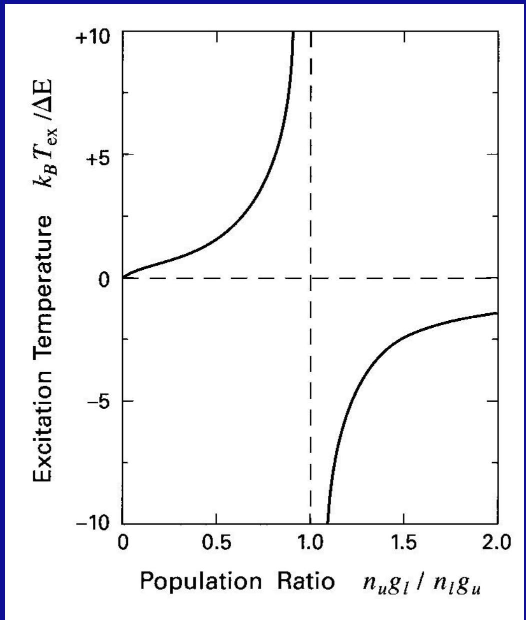
→ Negative excitation temperatures

- 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

Stahler & Palla 2004



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

Rising T_{ex}

→ Level populations approach each other

→ Only “overcome the border”.

Pumping mechanisms, e.g.:

- Collisional pumping in shocks of protostellar jets for H_2O masers.
- Radiative pumping in shocks or from protostars (e.g., CH_3OH masers)

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

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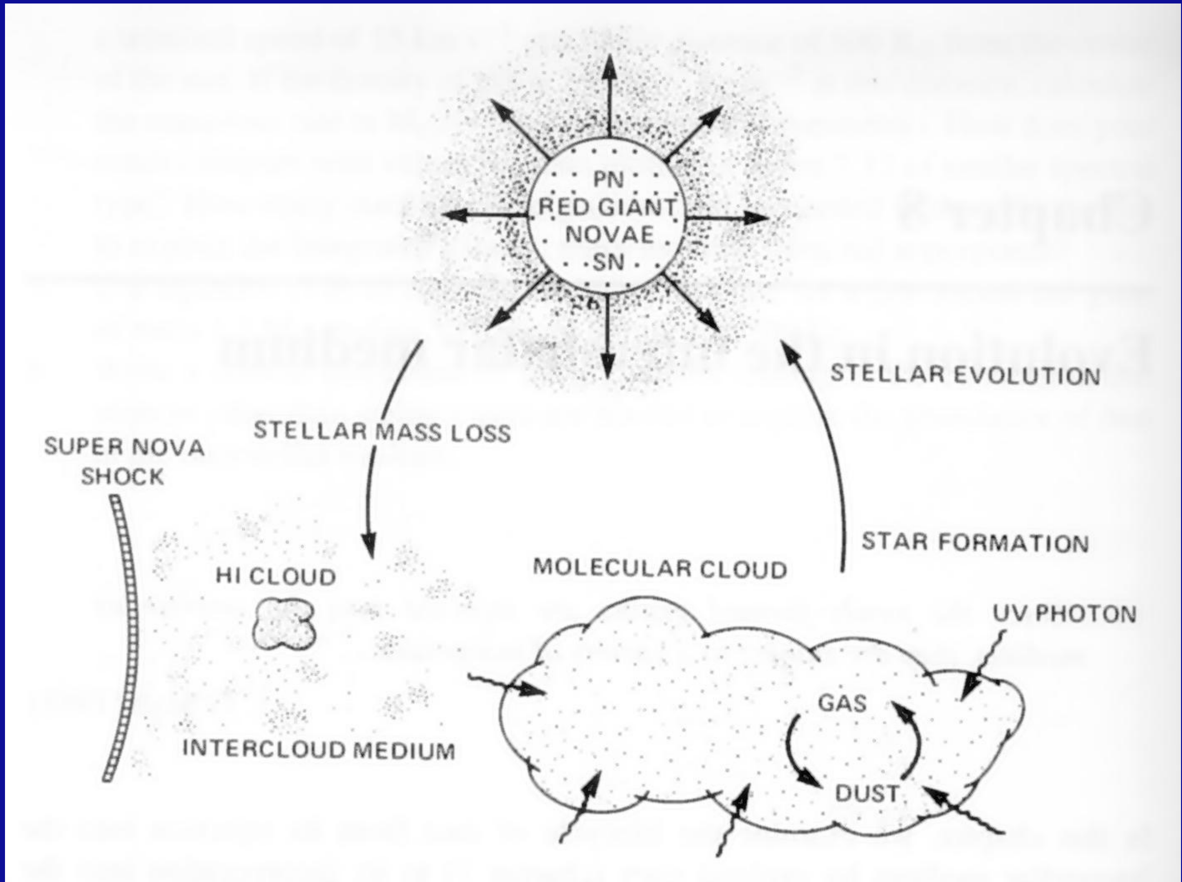
- Physical distributions (Maxwell, Planck, Boltzmann, Saha)

Dust within the big circle of matter



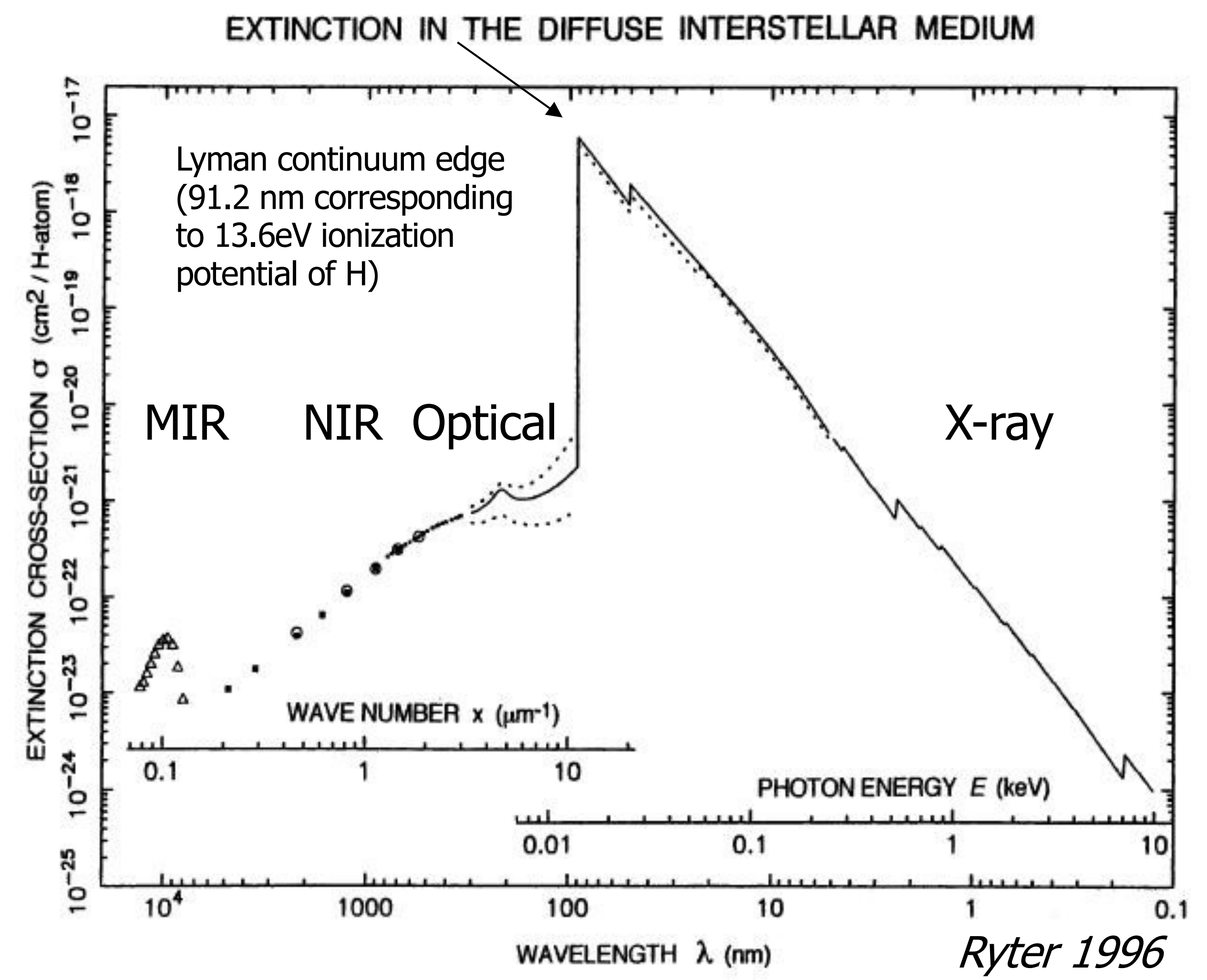
<u>Dust composition:</u>
Graphite/carbon C
Silicon carbide SiC
Enstatite $(Fe,Mg)SiO_3$
Olivine $(Fe,Mg)_2SiO_4$
Iron Fe
Magnetite Fe_3O_4

<u>Size distribution:</u>
Between 0.005 and 1μm
$n(a) \sim a^{-3.5}$ (a: size)
(Mathis, Rumpl, Nordsieck 1977)

<u>Gas to dust mass ratio:</u>
Canonical 1:100
Recent work suggests
1:150 (Draine et al. 2011)

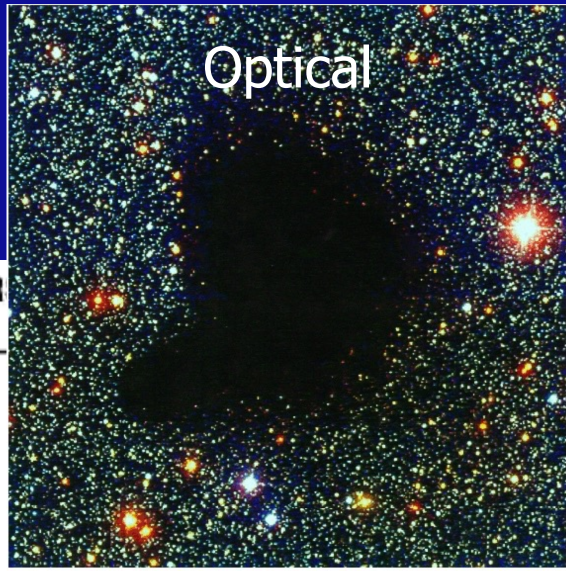
<u>Producers:</u>
- Outer atmosph. of Red Giants, Planetary Nebulae (PN)
- Supernovae (SN)
- More recent: Dust can also form in the general interstellar medium (ISM).

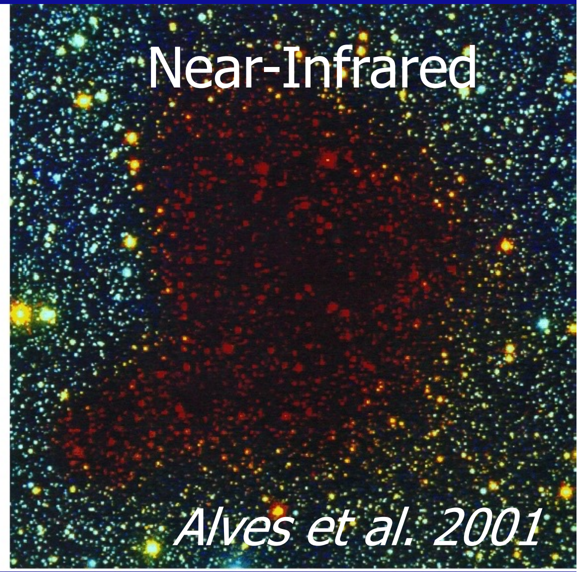
Interstellar dust: Extinction at shorter wavelengths

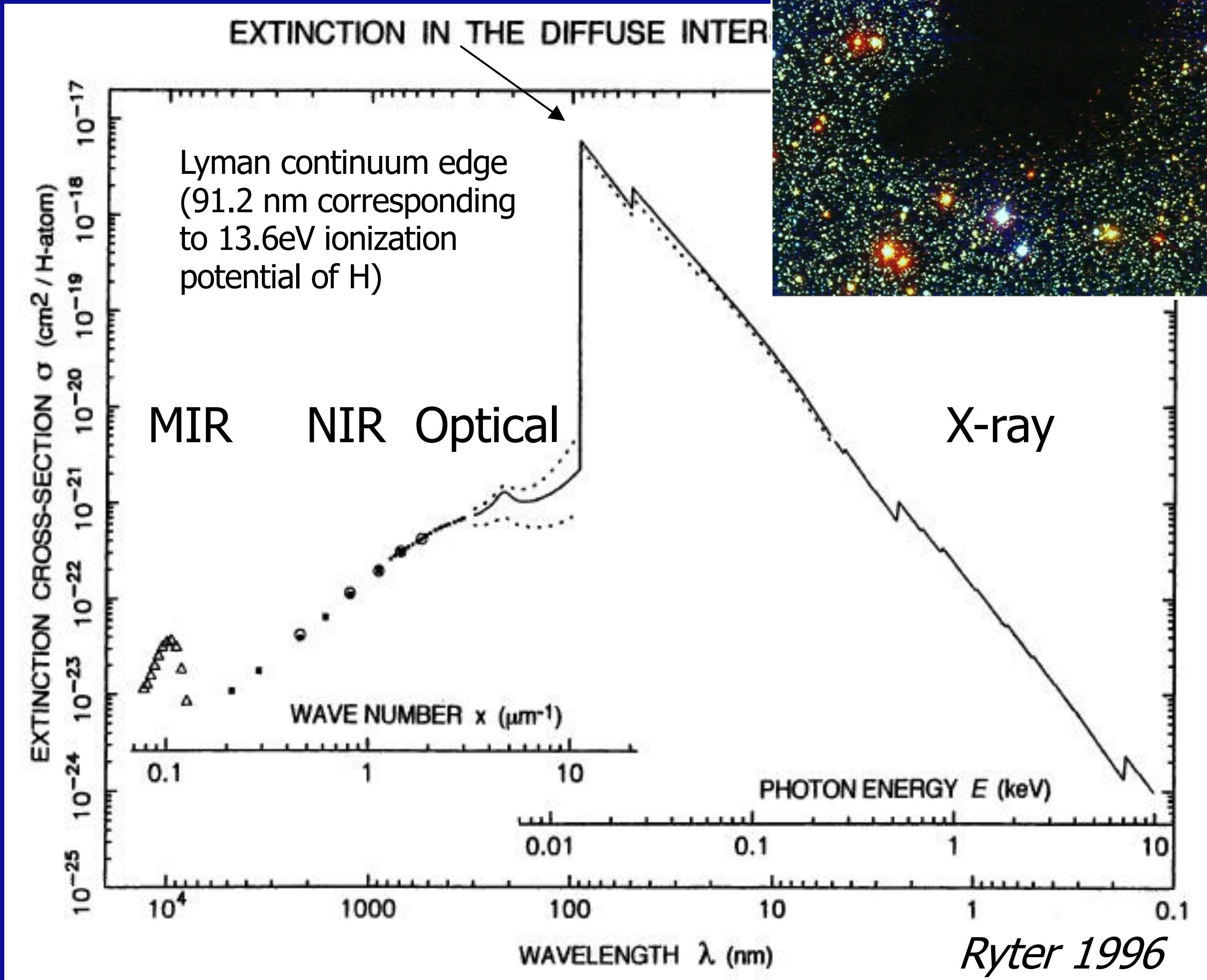


Extinction dims *and* reddens the light

Interstellar dust: Extinction at shorter wavelengths

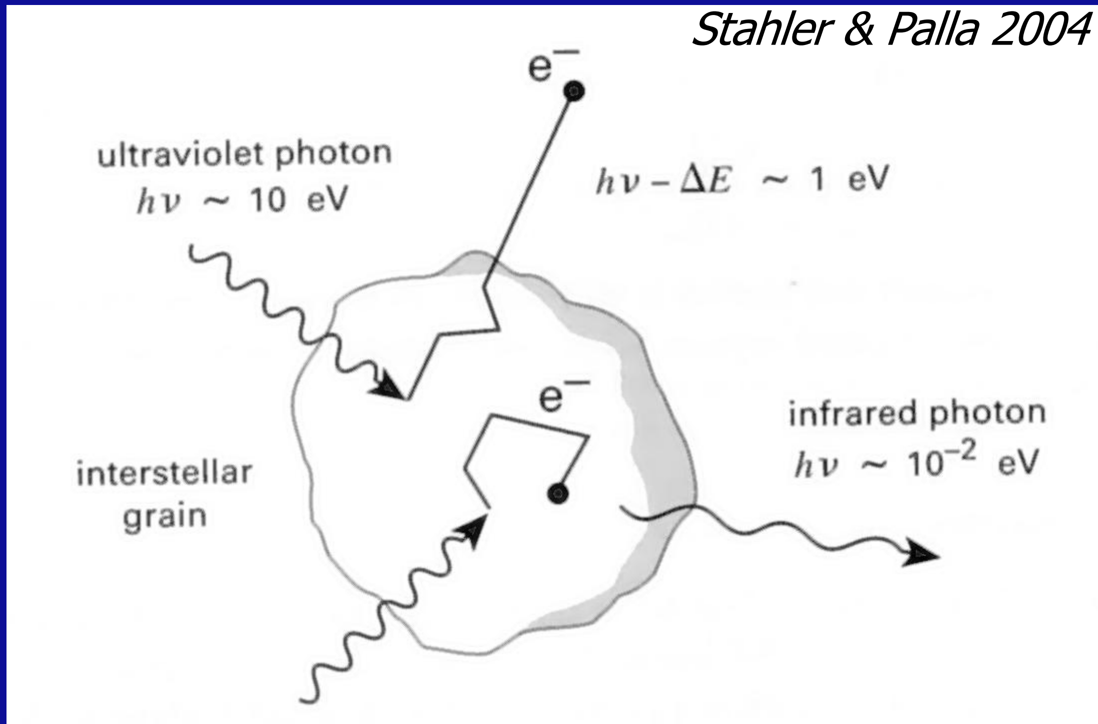






Extinction dims *and* reddens the light

Dust action at longer wavelengths: Re-emission



Dust grain hit by UV photon:

1) Photoelectrical effect → give energy to e^- → leaves grain and heats gas.

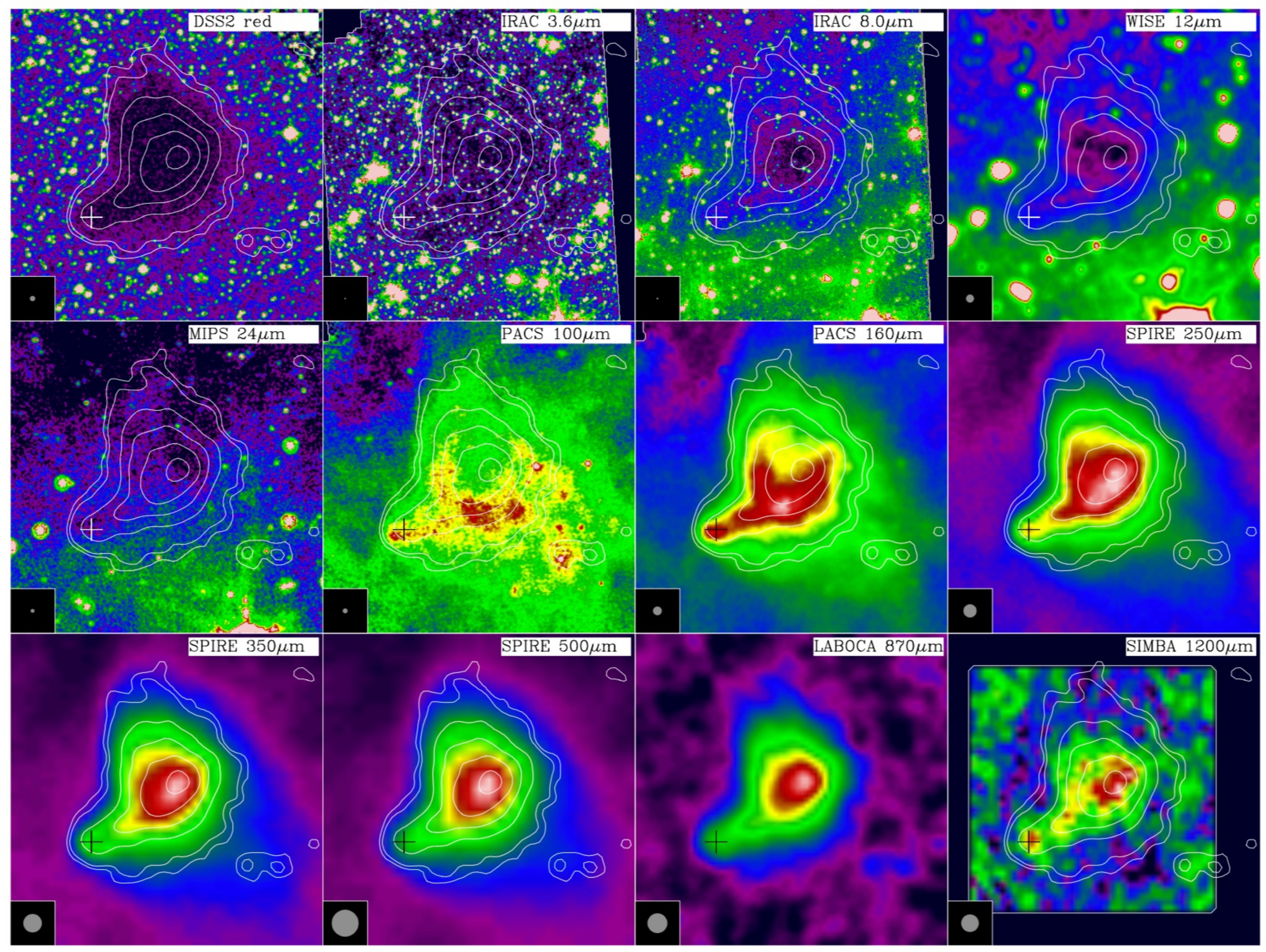
2) Excites lattice vibrations → transformed to (far)-IR photons and re-emitted.

Dust action at longer wavelengths: Re-emission

Dust g

1) Ph gas.

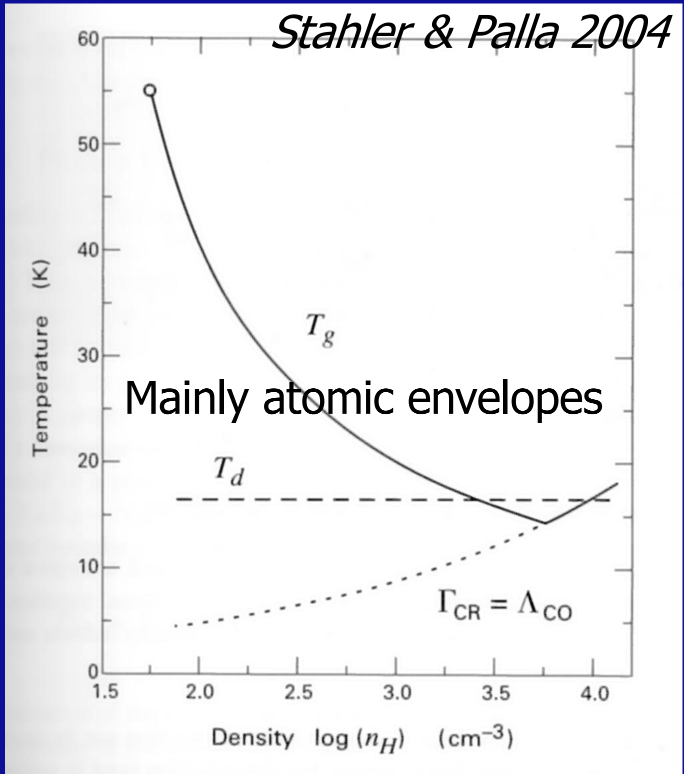
2) Ex emitted.



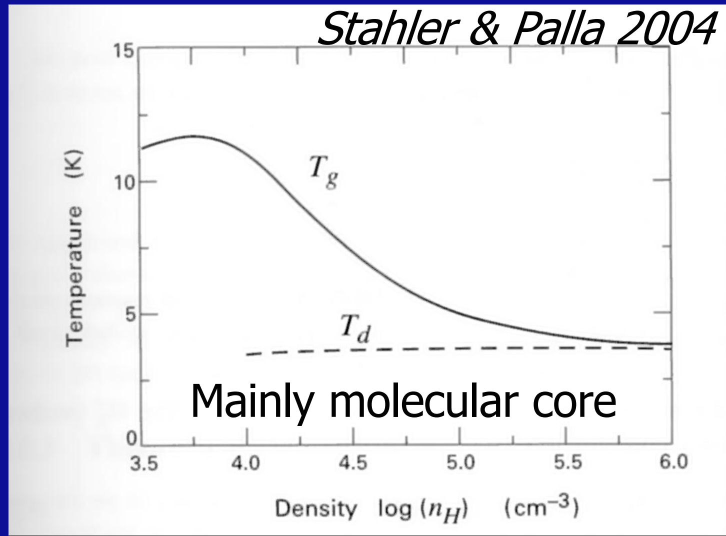
Nielbock et al. 2012, Contours 870μm

Continue next week

Dust and gas coupling



Cosmic ray heating more sensitive to density than CO cooling. Hence T_g rises again.



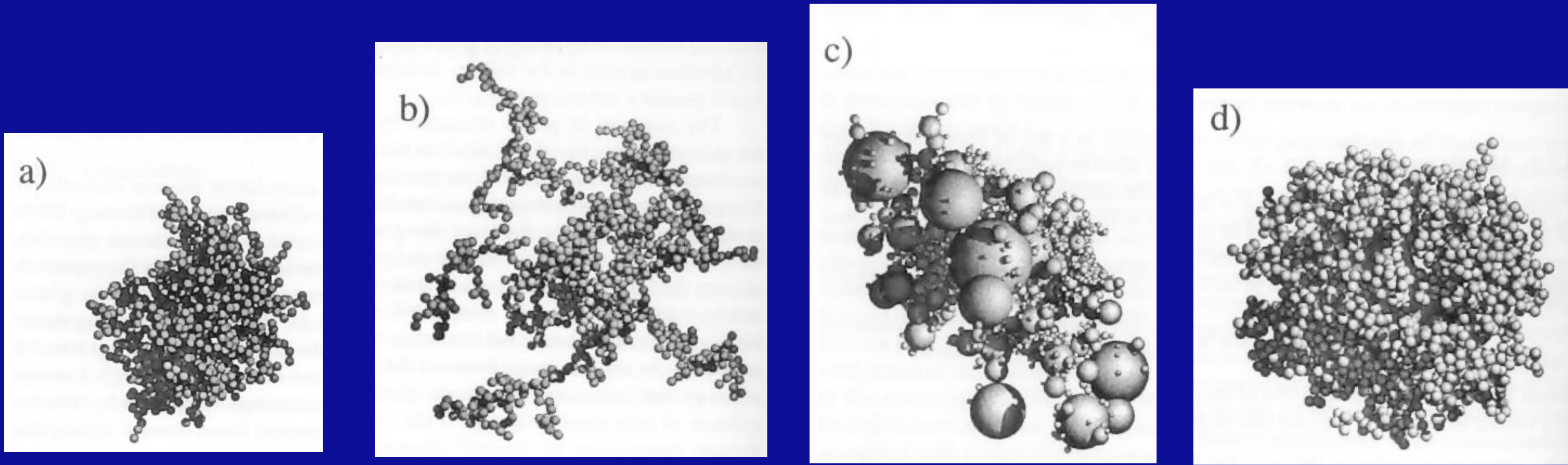
simplified model → lowest obs. T_d ~ 7-10K

Γ – heating rate Λ – Cooling rate

- Low densities: gas and dust de-coupled; at high densities coupled.
- Low densities gas cooling mainly CO; high densities via CO & dust.
- At very high densities gas and dust temperatures approach each other

→ CO cooling becomes insignificant then!

Dust incarnations



Dust can grow and coagulate in very dense environments, e.g., disks.

Figures: Simulations of dust grain cluster growth for different initial parameters (gas and dust density, temperature, stickyness, grain charge, coagulation time …).
(From Dorschner & Henning 1995)

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- Line profiles and a few applications for line emission

- Magnetic field measurements (Zeeman and dust)

- Maser emission

- Dust properties

- Physical distributions (Maxwell, Planck, Boltzmann, Saha)
---> shifted to next week

Summary

- Line profiles (thermal and kinematic broadening) and some applications

- Magnetic fields are very important but difficult to measure:
    - Zeeman effect traces **B** component along line of sight.
    - Dust polarication traces **B** in plane of the sky.
      (Other magnetic field measurements possible.)

- Masers are non-thermal processes. Good for high spatial accuracy and proper motion studies.

- Dust important from many points of view:
    - Traces warm and cold components of ISM.
    - Important coolant at high densities.
    - Traces magnetic field.
    - Chemical catalyst.

- Physical distributions and their applicability to the ISM.

Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

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More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html

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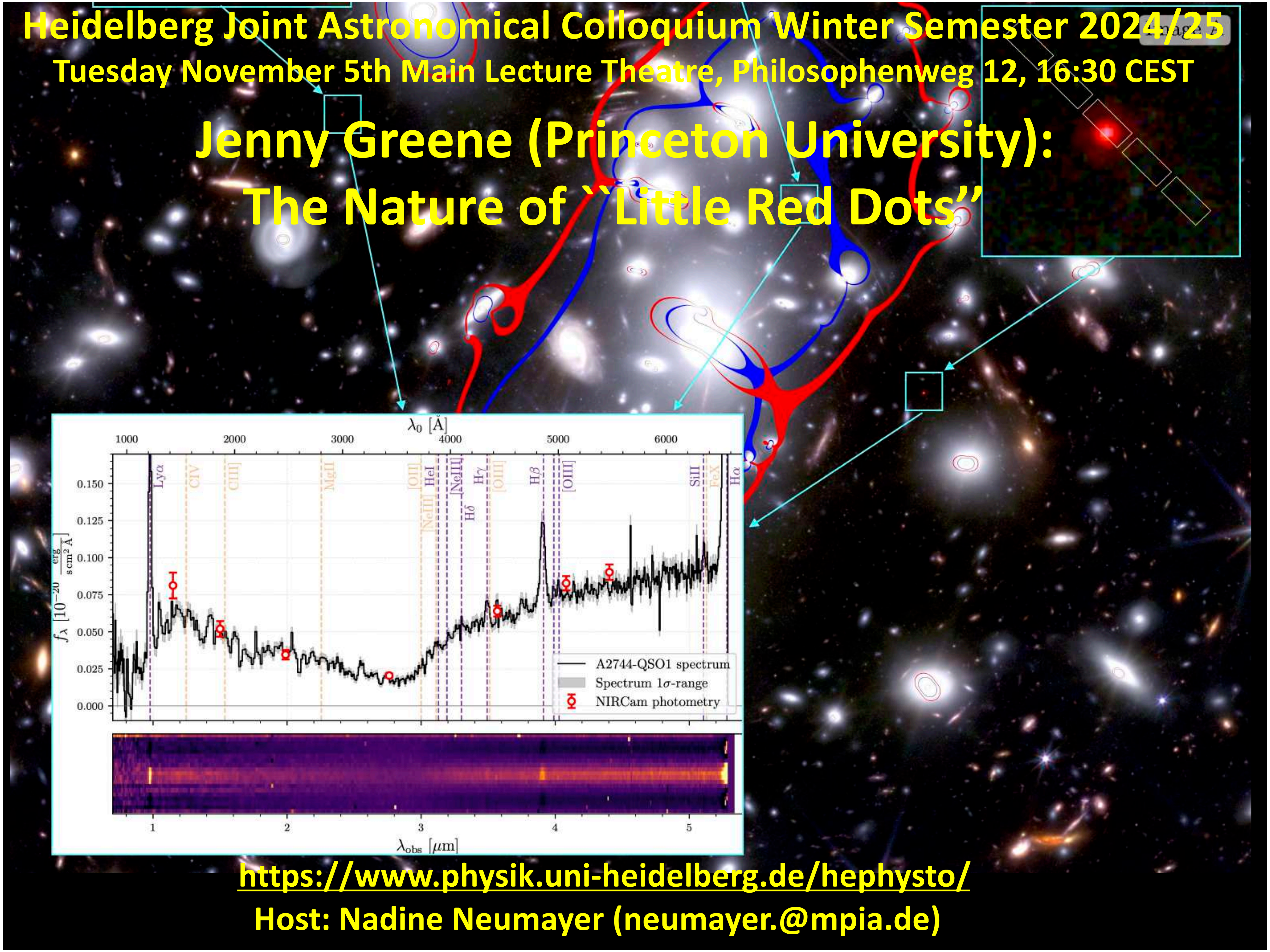
Heidelberg Joint Astronomical Colloquium Winter Semester 2024/25

Tuesday November 5th Main Lecture Theatre, Philosophenweg 12, 16:30 CEST

Jenny Greene (Princeton University): The Nature of ``Little Red Dots''



https://www.physik.uni-heidelberg.de/hephysto/

Host: Nadine Neumayer (neumayer.@mpia.de)