Stern- und Planetenentstehung
Sommersemester 2020
Markus Röllig

Lecture 1: Observing the Cold ISM

http://exp-astro.physik.uni-frankfurt.de/star_formation/index.php

Vorlesung/Lecture

Raum: Physik - 02.201a

dienstags, 12:00(c.t.) - 12:00 Uhr

Sprechstunde:

Raum: GSC, 1/34, Tel.: 47433, (roellig@ph1.uni-koeln.de)

dienstags: 14:00-16:00 Uhr

Nr.	Thema	Termin
1	Observing the cold ISM	21.04.2020
2	Observing Young Stars	28.04.2020
3	Gas Flows and Turbulence Magnetic Fields and Magnetized Turbulence	05.05.2020
4	Gravitational Instability and Collapse	12.05.2020
5	Stellar Feedback	19.05.2020
6	Giant Molecular Clouds	26.05.2020
7	Star Formation Rate at Galactic Scales	02.06.2020
8	Stellar Clustering	09.06.2020
9	Initial Mass Function – Observations and Theory	16.06.2020
10	Massive Star Formation	23.06.2020
11	Protostellar disks and outflows – observations and theory	30.06.2020
12	Protostar Formation and Evolution	07.07.2020
13	Late Stage stars and disks – planet formation	14.07.2020

1 Observing the cold ISM

„SF is perhaps the least understood process in cosmic evolution.“ (M. Krumholz)

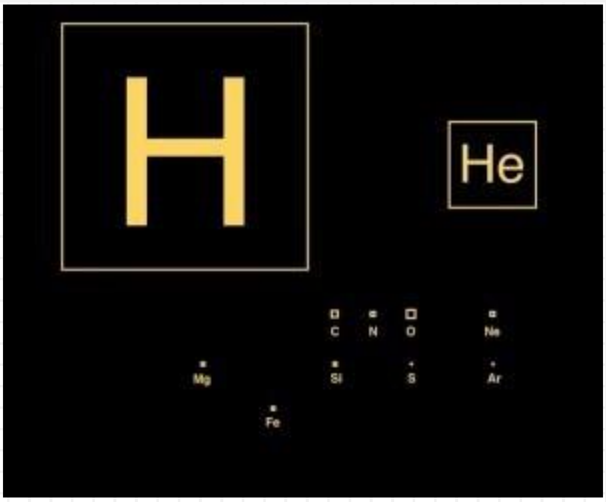
- Wide range of physical processes involved
  → general theory difficult to formulate
- Interstellar gas out of which stars form is a supersonically turbulent plasma → MHD
  (we hardly understand subsonic hydrodynamic turbulence)
- SF influenced by gravity → added complexity
- ISM is a radiative fluid
  (continuum and line radiative processes)
- SF(ISM influenced by chemistry
  (formation & destruction of molecules & dust grains
  → changed TD of gas
- Variation of ionization state → coupling to magnetic fields

Comparison: stellar structure is governed by 4 equations!

1.1 Observing Techniques

1.1.1 Observing H_2

Hydrogen is the most abundant element



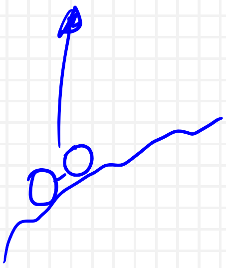
briankoberlein.com

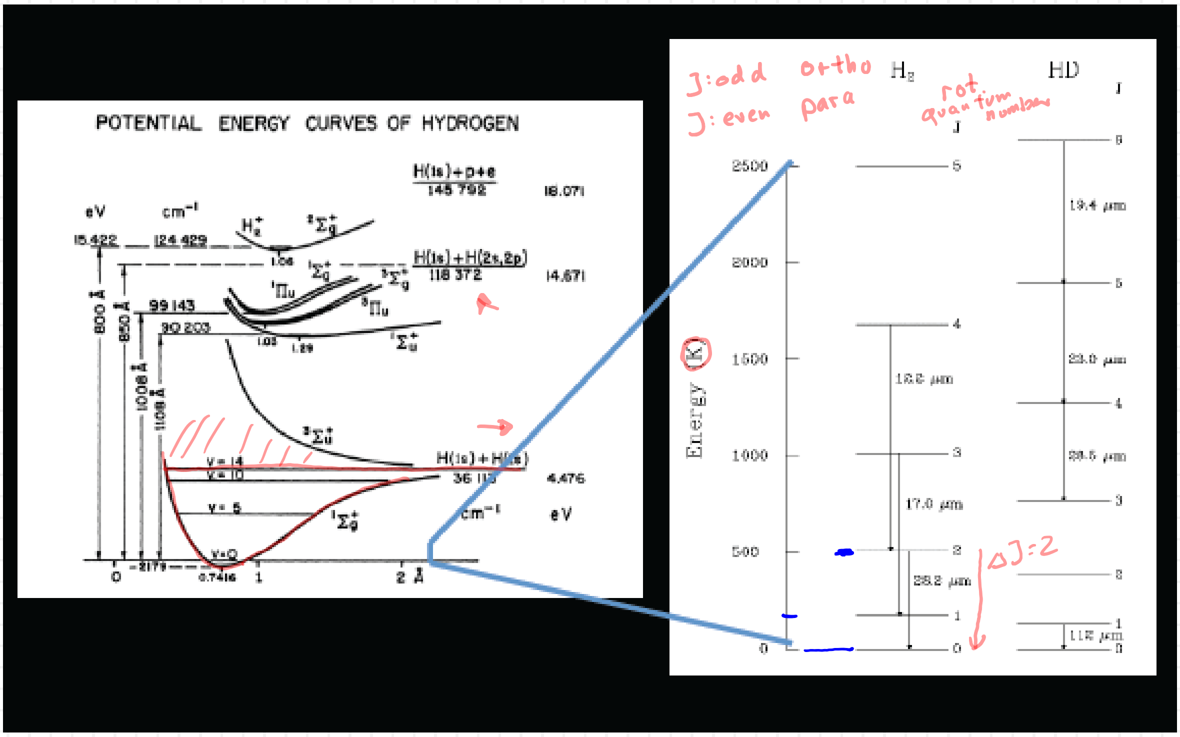
- Atomic H
  - easy to observe
  - hyperfine transition @ 21 cm (1.4 GHz)
    e- spin parallel to p-spin => anti-parallel
    $\Delta E << 1$ K => can be excited everywhere

e-spin ↑ ↑ p-spin
↑ ↓
=> easy to excite

- Molecular H_2
  - @ high densities H → H_2
  - H2 extremely hard to observe directly

$n \gtrsim 100 \text{ cm}^{-2}$





excitation of diatomic molecule (high to low energy)

- electronic
- vibrational
- rotational

$E_{rot} < E_{vib} < E_{el.}$

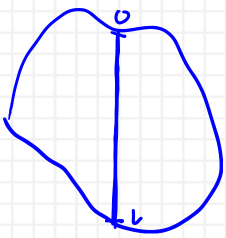
Credit: NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)

- H_2: first excited state J=1 (E=100-200K)
  $T_{\text{dense ISM}}$ ~ 10 K => very few > H_2 molecules in J=1
- H_2 homo-nuclear molecule
  - μ = 0 (electr. dipole moment)
  - no electr. dipole transitions (ΔJ=1) ±
    quadrupole transitions (ΔJ=2) ±

$$\Delta E \sim \frac{1}{\sqrt{m_{red}}}$$

light species – large level spacing

$\int_0^L n(z)\,dz = N$ cm^{-2} (L, cm^{-3})



ground state transition: J=2-0   para

J=3-1   ortho

E(J=2)=511 K => @ 10K $\frac{n_{J=2}}{n_{J=0}} \sim e^{-\frac{511\,K}{10\,K}} \approx 10^{-22}$

typical column densities ~ 10^{22} (only one H_2 excited!)

most abundant species unobservable → proxy species

CO, ^{13}CO, $C^{18}O$

1.1.2 Dust Emission (thermal)

ISM: mixture of gas & dust

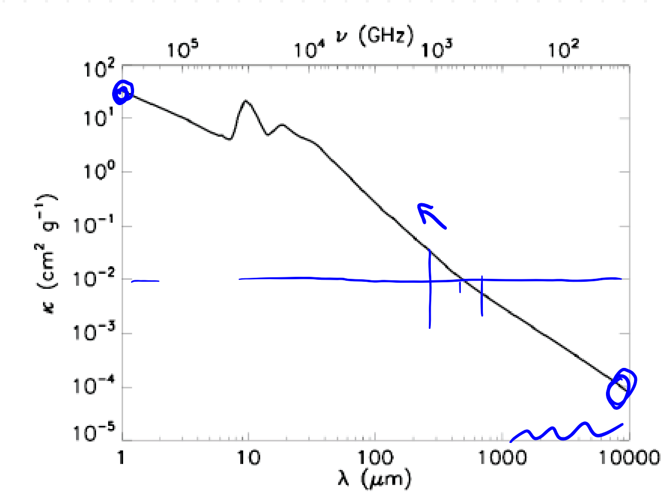
Dust: emits thermal (continuum) radiation (black body)
Gas: emits line radiation

Cloud of gas ρ : mass density g/cm^3 n : particle density cm^{-3}
mixed with dust @ temperature T

⇒Gas and dust mixture has opacity κ_ν to radiation at frequency ν
⇒Most of the mass in gas
⇒Most of the opacity due to dust (except at line frequencies)

Convention: κ_ν : opacity per gram of material with units of $cm^2\,g^{-1}$

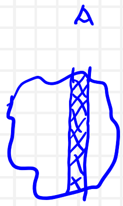
effective cross sectional area that is blocked per gram of gas
sub-mm: typically $\kappa_\nu \sim 0.01\ \mathrm{cm^2 g^{-1}}$



Draine 2003

surface density $\cancel{M_H m} = \Sigma_{\mathrm{H}}$ $\frac{g}{cm^2}$

optical depth $\tau_{ext} = \Sigma_H \kappa_\nu$



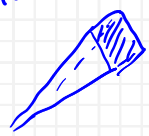
absorption if $\tau_{ext} > 1$

but no cloud with $100 \cdot 10^{-2} \approx 1$

$$\Sigma_{\mathrm{H}} > 100 \mathrm{~g~cm^{-2}}$$

⇨ cloud is optically thin to its thermal radiation

sr : steradian solid angle 4π



⇨ emitted intensity

emissivity of gas of opacity κ_ν

$$j_\nu = \kappa_\nu\, \rho\, B_\nu(T) \;\; \mathrm{erg\,s^{-1}cm^{-3}sr^{-1}Hz^{-1}}$$

energy (erg) emitted in 1 sec by 1 cm³ of gas into a solid angle of 1 steradian (sr) in a frequency range of 1 Hz.

$$B_\nu(T) = \frac{2\,h\,\nu^3}{c^2}\frac{1}{e^{\frac{h\,\nu}{k\,T}} - 1} \;\; \mathrm{erg\,s^{-1}cm^{-2}sr^{-1}Hz^{-1}}$$ Planck

specific intensity

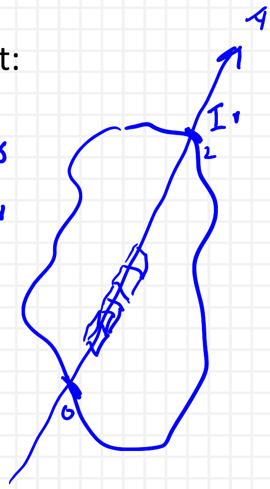
No radiation absorbed => intensity transmitted along a given line of sight:

$$I_\nu = \int j_\nu ds = \int \kappa_\nu\, \rho\, B_\nu(T)\, ds$$

$$= \Sigma\, \kappa_\nu\, B_\nu(T) = \tau_\nu\, B_\nu(T)$$

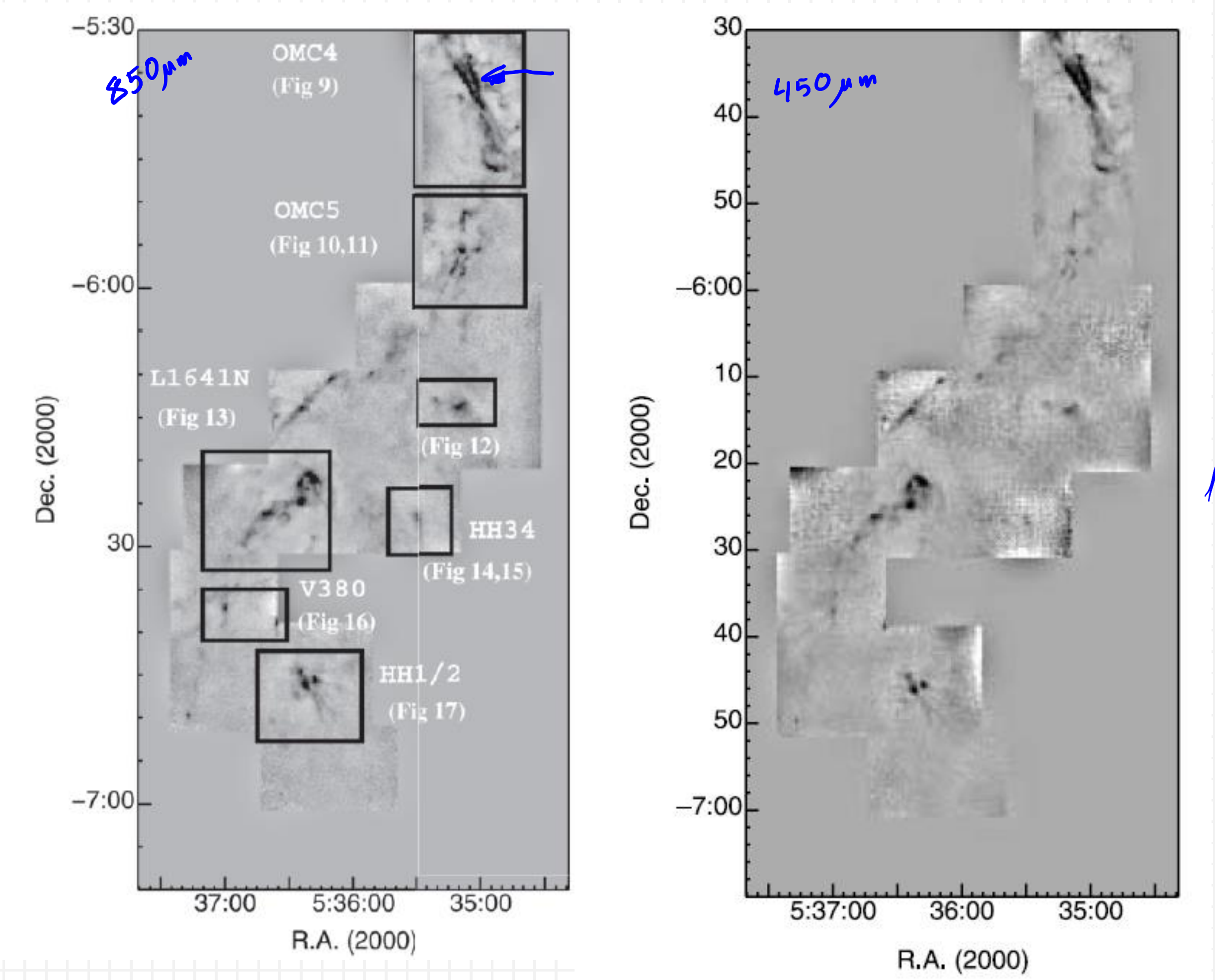
$\int \cancel{\rho} \rho\, ds$

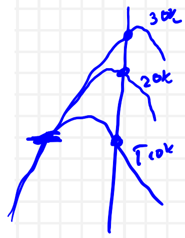
$\Sigma \cdot$ ~~...~~



τ_ν : optical depth along the line of sight at frequency ν

$$\tau_\nu = \int_0^L \kappa_\nu(l) dl$$





Thermal dust emission map of Orion A south at 850µm (left) and at 450µm (right). (Johnstone and Bally 2006)

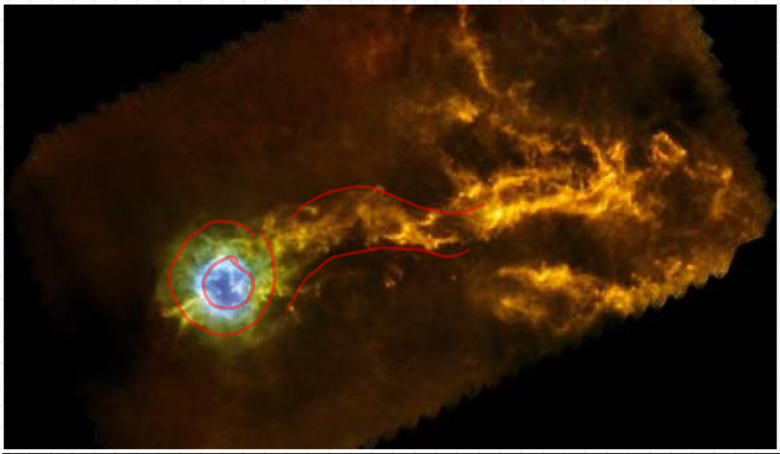
observe at various λ → fit N, κ_ν, and T simultaneously

2009

Before Herschel:

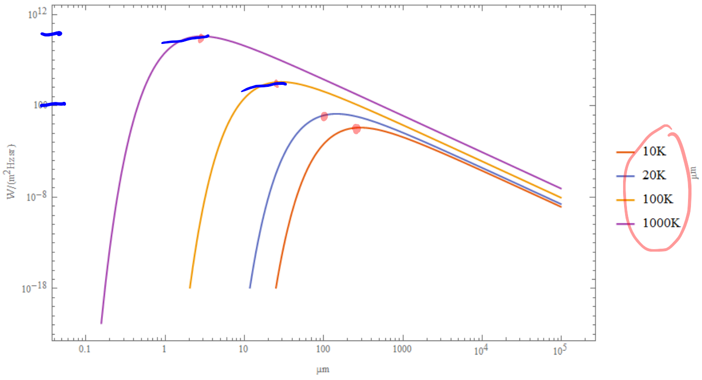
very little multi λ data

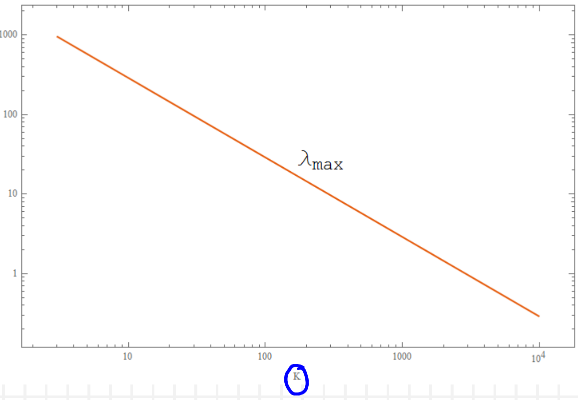
because most emission in FIR



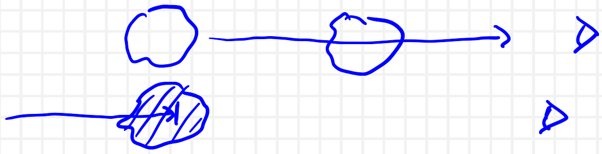
Composite 3-color image of IC 5146 (~1.6 deg2 field) produced from our PACS/SPIRE parallel-mode data at 70, 160, 250, 350 and 500 µm. The color coding is such that red = SPIRE 500 µm and 350 µm, green = SPIRE 250 µm and PACS 160 µm, blue = PACS 70 µm.

(Arzoumanian et al. 2011)

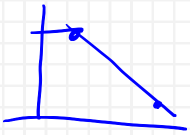




1.1.3 Dust Absorption

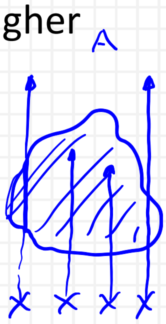


Instead of observing emission by dust → absorption by dust against background stars



Pro

1. stars are bright & observation in near IR → resolution much higher
2. κ_ν is no function of T → uncertainty of T does not matter
3. κ_ν in IR much better known than in sub-mm



Con

1. $\kappa_\nu(IR) \gg \kappa_\nu(FIR)$ → only applicable to diffuse clouds (dense fields absorb completely)

   see Bok globules

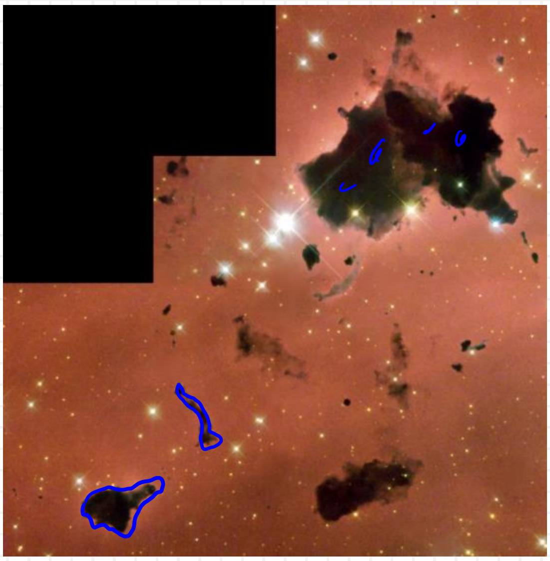
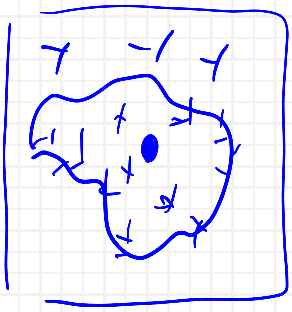
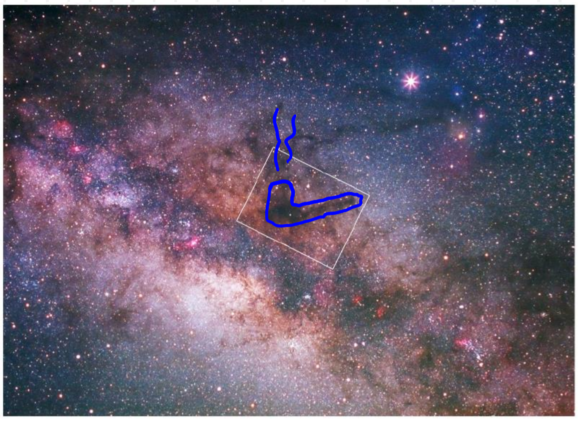


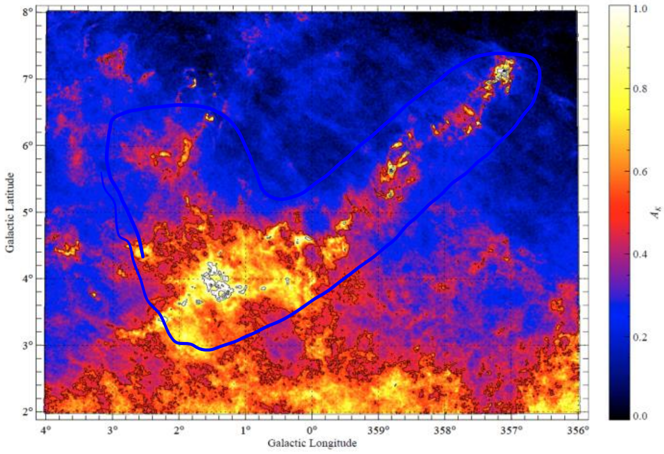
Abbildung 1 Thackeray's Globules: Dense, Opaque Dust

2. field of background stars required



Best example: Pipe nebula

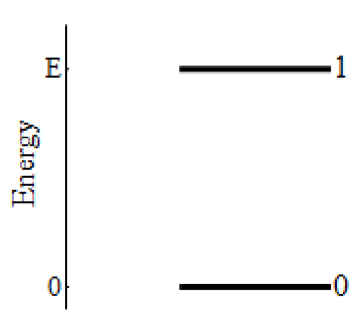




Pipe nebula extinction map (right) (Lombardi et al. 2006)

1.1.4 Molecular Lines

- Most info about SF from molecular lines
- Complex modelling necessary to interpret lines
- Rich in information
- Most sensitive
- Almost everything we know about GMCs outside of the Milky Way comes from studying emission in rot. lines of CO.



number densities: n_0, n_1

2-level molecule

1.1.4.1 *No radiation – only collisions*

eventually thermal equilibrium (TE) => (Maxwell-)Boltzmann Distribution

$$\boxed{\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E}{k\,T}}}$$

2-lev system

$g_0 = 1, g_1 = 1$

$n_1 = \frac{n_{tot}}{Z} \cdot e^{-E/kT}$

$$n_0 = \frac{n_{tot}}{Z} = \frac{n_{tot} \cdot \cancel{e^{-\frac{E}{kT}}}}{\sum_i g_i\, e_i^{-\frac{E_i}{k\,T}}}$$

0

Z: partition function

(Zustandssumme)

$g_0 \cdot e^{-\frac{E_0}{kT}}$

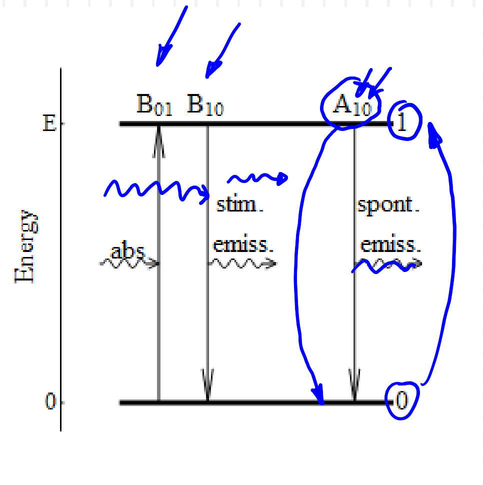
$$with\ E_0 = 0, E_1 = E, g_0 = 1, g_1 = 1 \Rightarrow \quad Z = 1 + e^{-\frac{E}{k\,T}} + \ldots$$

$$\boxed{n_1 = \frac{n_{tot}}{Z} e^{-\frac{E}{k\,T}}}$$

Boltzmann factor

$$e^{-\frac{E}{k\,T}}$$

1.1.4.2 *Radiative transitions*



- spontaneous emission
- stimulated emission
- absorption

⇨ no external radiation field

⇨ ignoring B_{10}, B_{01}

Particle in an excited state can emit a photon and decay

Rate: $\left(\frac{dn1}{dt}\right)_{\text{spont. emission}} = -A_{10} \cdot n_1$ (particles $cm^{-3}\ s^{-1}$)

$[A] = \frac{1}{s}$ $\qquad {}^{1}/_{A}$: e-folding time for decay

$$\boxed{\frac{dn_1}{dt} = -A_{10} n_1} \quad => \frac{dn_1}{n_1} = -A_{10} dt$$

$$\int_{n_{1,i}}^{n_{1,f}} \frac{dn_1}{n_1} = \int_{t=0}^{t_1} -A_{10} dt$$

$$\ln(n_{1,f}) - \ln(n_{1,i}) = -A_{10} t - 0$$

$$\ln\left(\frac{n_{1,f}}{n_{1,i}}\right) = -A_{10} t \quad => \frac{n_{1,f}}{n_{1,i}} = \exp(-A_{10} t)$$

if $t \rightarrow 1/A_{10}$ $\quad \frac{n_{1,f}}{n_{1,i}} = \exp\left(-\frac{A_{10}}{A_{10}}\right) = \frac{1}{e} = 0.37$

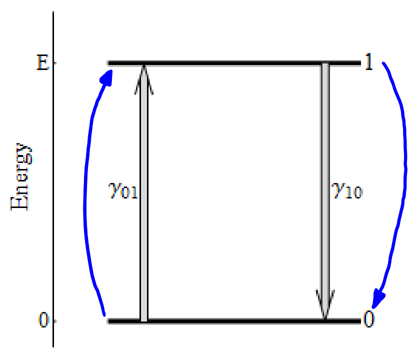
after $1/A_{10}$ sec., 63% of excited states are decayed

E.g: CO J=1-0 $A = 7.2 \times 10^{-8}\ \mathrm{s}^{-1}$

HI, 21 cm line $A \cong 10^{-15}\ \mathrm{s}^{-1} = 3 \times 10^{7}\mathrm{a}$

1.1.4.3 Radiative and collisional transitions

Cold ISM: H_2 is dominant collision partner



γ_{01}: rate coefficient for $[\mathrm{cm}^3\mathrm{s}^{-1}]$ for collisional excitation (difficult to compute -> exp)

γ_{10}: rate coefficient for $[\mathrm{cm}^3\mathrm{s}^{-1}]$ for collisional de-excitation

$$\left(\frac{dn_1}{dt}\right)_{coll.exc.} = \gamma_{01}\, n_{H_2}\, n_0$$

n_{H_2}: number density of H_2 (coll. partner)

$$\left(\frac{dn_1}{dt}\right)_{coll.de-exc.} = -\gamma_{10}\, n_{H_2}\, n_1$$

E

In equilibrium:

$$\frac{dn_1}{dt} = \left(\frac{dn_1}{dt}\right)_{coll.exc} + \left(\frac{dn_1}{dt}\right)_{coll.de-exc} = 0$$

$$\underset{H_2}{n}(\gamma_{01}\, n_0 - \gamma_{10}\, n_1) = 0$$

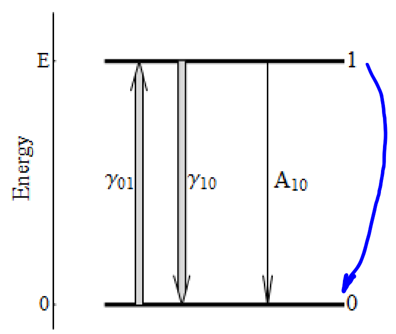
$$\boxed{\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E}{kt}}}$$

$$n(\gamma_{01}\, n_0 - \gamma_{10}\, n_1) = \cancel{n}\, n_0 \left(\gamma_{01} - \gamma_{10}\boxed{\frac{n_1}{n_0}}\right) = 0$$

$$\gamma_{01} = \gamma_{10}\boxed{\frac{g_1}{g_0} e^{-\frac{E}{k\,T}}}$$

CRITICAL DENSITY AND DENSITY INFERENCE

Full equation of statistical equilibrium for 2 level-system



$$\frac{dn_1}{dt} = 0$$

$$\boxed{n_1 A_{10}} + \boxed{n\, n_1 \gamma_{10}} - \boxed{n\, n_0 \gamma_{01}} = 0$$

$$\frac{n_1}{n_0}(A_{10} + \gamma_{10} n) - \gamma_{01} n = 0$$

$$\boxed{\frac{n_1}{n_0} = \frac{\gamma_{01} n}{A_{10} + \gamma_{10} n}} = \frac{\gamma_{01} n}{\gamma_{10} n} \frac{1}{1 + \frac{A_{10}}{\gamma_{10} n}}$$

$$\boxed{\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E}{k\,T}} \frac{1}{1 + \frac{A_{10}}{\gamma_{10} n}}}$$

If $A_{10} \ll \gamma_{10} n$ => radiation is unimportant => TE when $A_{10}/\gamma_{10}n$ increases radiation becomes more important

population in n_1 drops

=> population is subthermal

Balance between A_{10} and γ_{10} depends on n!

if $A_{10} = \gamma_{10} n$

$$\boxed{n_{crit} = \frac{A_{10}}{\gamma_{10}}}$$

$$1 = \frac{A_{10}}{\gamma_{10} \cdot n} \qquad n = \frac{A_{10}}{\gamma_{10}}$$

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E}{kT}} \frac{1}{1 + \frac{n_{crit}}{n}}$$

If n=n_{crit} collisional excitation and radiative decay are equal

n > n_{crit} : level population -> Boltzmann

n < n_{crit} : level underpopulated rel. to Boltzmann

-> consequences for line emission

Line emission per molecule:

$$\frac{\mathcal{L}}{n_{tot}} = \frac{E A_{10} n_1}{n_{tot}} = \frac{E A_{10} n_1}{n_0 + n_1} = \frac{E A_{10} \left(\frac{n_1}{n_0}\right)}{1 + \left(\frac{n_1}{n_0}\right)}$$

$$= E A_{10} \frac{e^{-\frac{E}{k T}}}{1 + \frac{n_{crit}}{n}} \frac{1}{1 + \frac{e^{-\frac{E}{k T}}}{1 + \frac{n_{crit}}{n}}} = E A_{10} \frac{e^{-\frac{E}{k T}}}{e^{-\frac{E}{kT}} + 1 + \frac{n_{crit}}{n}}$$

$$= \boxed{E A_{10} \frac{e^{-\frac{E}{k T}}}{Z + \frac{n_{crit}}{n}}}$$

$$n \ll n_{crit} \quad \Rightarrow Z + \frac{n_{crit}}{n} \rightarrow \frac{n_{crit}}{n} \quad \Rightarrow \boxed{\frac{\mathcal{L}}{n_{tot}} \approx E\, A_{10}\, e^{-\frac{E}{kT}} \left(\frac{n}{n_{crit}}\right)}$$

Low densities: each molecule contributes an amount of energy proportional to the ratio of $\frac{n}{n_{crit}}$

n: H_2 density => $\frac{\mathcal{L}}{n_{tot}}$ independent of n_{tot} but not of n

$$\boxed{\mathcal{L} \propto n_{tot} \times \frac{n}{n_{crit}}}$$

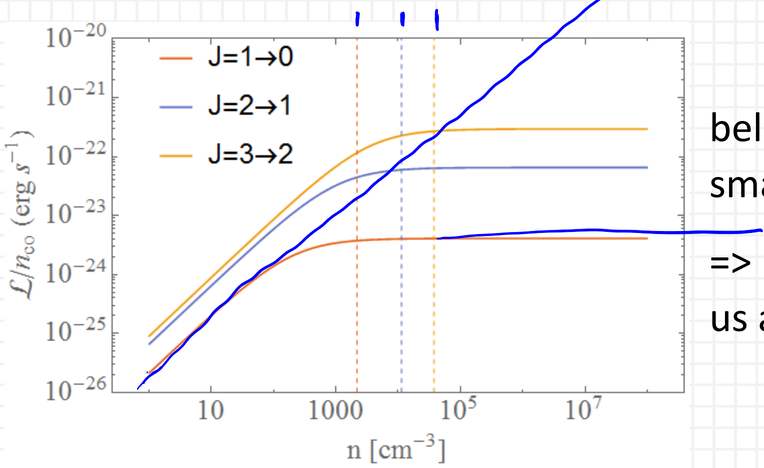
(every molecule emits)

$\boxed{n \gg n_{crit}}$ => Z dominates denominator

$$\Rightarrow \frac{\mathcal{L}}{n_{tot}} \approx E\, A_{10} \frac{e^{-\frac{E}{kT}}}{Z}$$

$\frac{n_1}{n_{tot}}$ fraction of population in upper state

density independent => at given T we get a fixed amount of energy

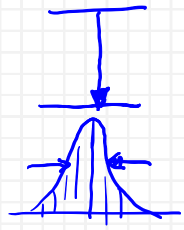


below n_{crit} intensity is usually too small to be observable

=> observing molecular lines tells us about density

VELOCITY AND TEMPERATURE INFERENCE

prerequisite: opt. thin → line width determined by velocity distribution of emitting molecules



assume vel. distr. $\psi(v)$,

then the fraction of gas with velocities between v and $v + dv$ is

$$\psi(v)dv \text{ and } \int_{\infty}^{\infty} \psi(v)dv = \cancel{0}\,1$$

in rest frame of molecule: emission -> delta function in frequency

gas moving at velocity v relative to us produces emission at frequency

$$\nu \approx \nu_0 (1 - \tfrac{v}{c}), \quad \tfrac{v}{c} \ll 1$$

where ν_0 is the rest frequency of the transition.

The line profile then is: $\phi(\nu) = \psi\left(c\left(1 - \frac{\nu}{\nu_0}\right)\right)$

Measuring $\phi(\nu)$ gives us $\psi(v)$

General: $\psi(v) = \psi_{thermal} + \psi_{non-thermal}$

$\psi_{thermal}$: Maxwellian velocity distribution $\phi(\nu) \propto e^{-(\nu-\nu_{cen})^2/\sigma_\nu^2}$

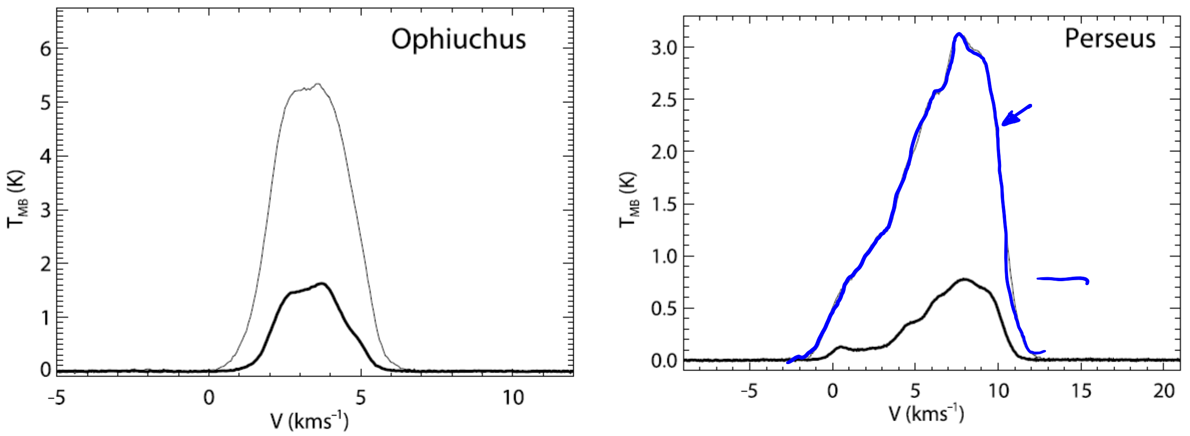
center frequency $\nu_{cen} = \nu_0\left(1 - \frac{\bar{v}}{c}\right)$

$\bar{v}$: mean velocity of gas along line of sight, σ_ν:width

$\sigma_\nu = \sqrt{(k\,T)/\mu}/c$ μ: mean mass of the emitting molecule

$\psi_{\text{non-}thermal}$:   bulk flows, shocks, outflows, etc.

even complicated motions resemble a Maxwellian distribution because of the central limit theorem



Ridhe et al. 2006

FIG. 13.—Average ^{12}CO (*thin lines*) and ^{13}CO (*thick lines*) spectra for Ophiuchus (*left*) and Perseus (*right*), created by summing the spectra in all pixels for which the ratio of peak antenna temperature to rms noise is greater than 3. The multicomponent nature of Perseus is clearly visible, while Ophiuchus displays a more Gaussian-like profile.

To determine whether an observed line profile is the result of predominantly thermal or non-thermal motion we need to derive the temperature independently.

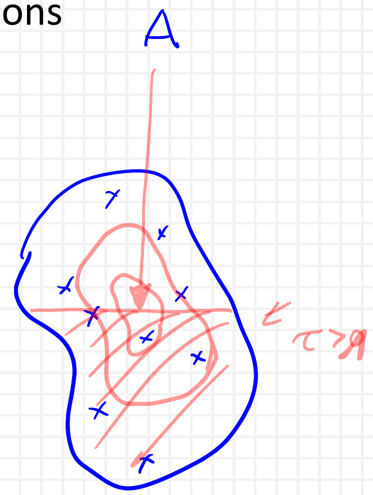
e.g.: observe multiple lines of the same species:

$$\boxed{\frac{\mathcal{L}}{n_{tot}} = E\,A_{10}\,\frac{e^{-\frac{E}{kT}}}{Z + \frac{n_{crit}}{n}}}$$

3 unknowns: T, n, n_{tot} observing 3 species => 3 equations

1.1.4.4 Complications

- optical depth
- chemistry (dissociation, freeze-out, formation, …)
- elemental abundances
- …



2 Observational Phenomology

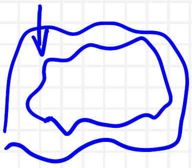
2.1 Giant Molecular Clouds

H_2 proxy: CO

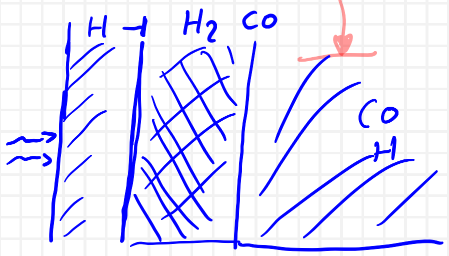
1) single most abundant molecule in the ISM
2) CO & H_2 coexist
3) CO easily excited $E(1-0) = 5.5K$

CO
J=2
5.5k J=1

problem: CO-dark-H_2 gas



HF $\quad F + H_2 \rightarrow HF + H$



HI

in the MW: HI:H2=70:30 varies with distance to GC

(~3kpc 1:1, 8kp 9:1)

HI neutral
HII H+

HI organized in filaments, molecular clouds at peaks

In spiral galaxies, the molecular gas closely follows the spiral structure

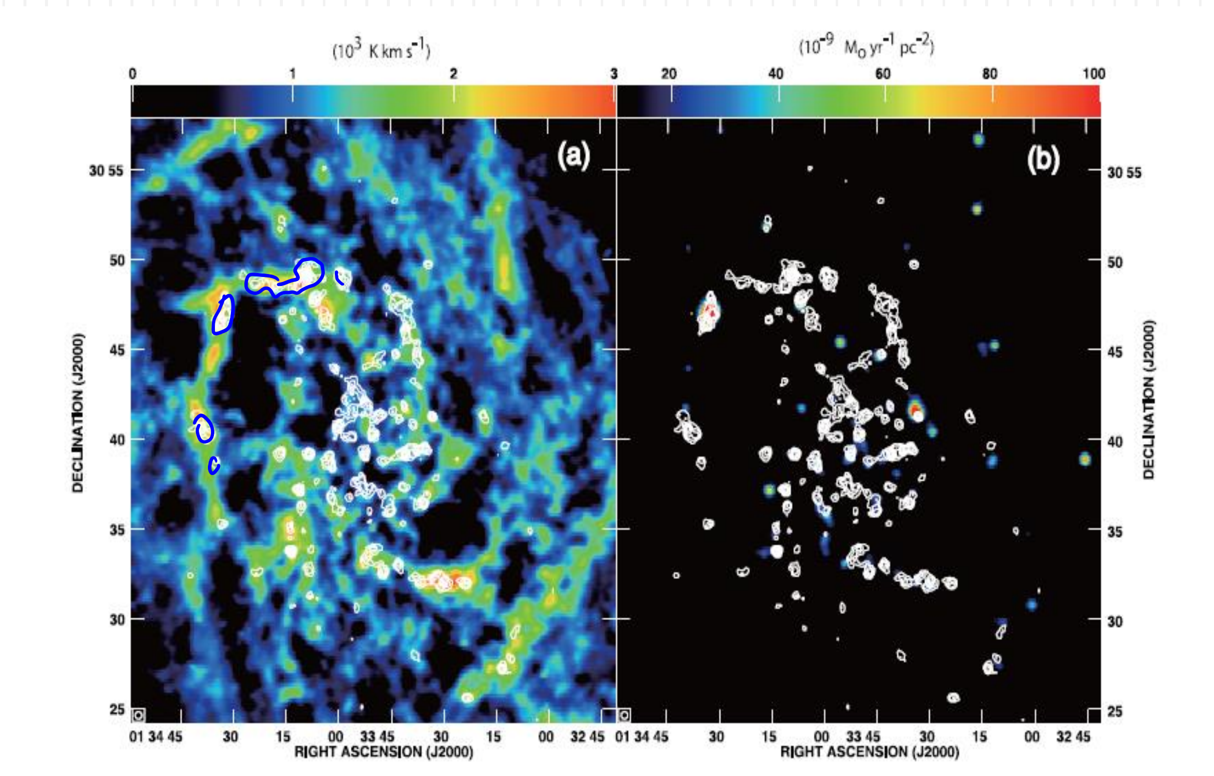


Fig. 3. Total integrated intensity map of [12]CO ($J = 1$–0) emission (contours) superposed on H I emission (left, Rosolowsky et al. 2007) and star-formation rate (right) derived from the Hα luminosity (Hoopes & Walterbos 2000) with extinction-correction by using MIPS 24 μm data (Rieke et al. 2004). The contour interval and lowest contour are the same as in figure 2.

Tosaki et al. 2011

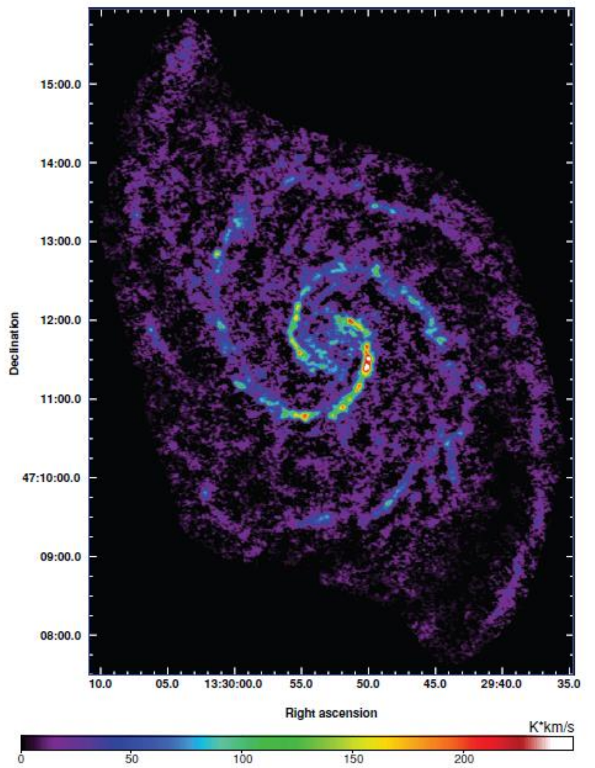


Figure 7. CARMA and NRO45 combined CO (J = 1–0) map of M51 with robust = −2.

Koda et al. 2011

molecular gas is organized in discreet clouds

Giant Molecular Clouds (GMC)

$M = 10^4 - 10^7 M_\odot$

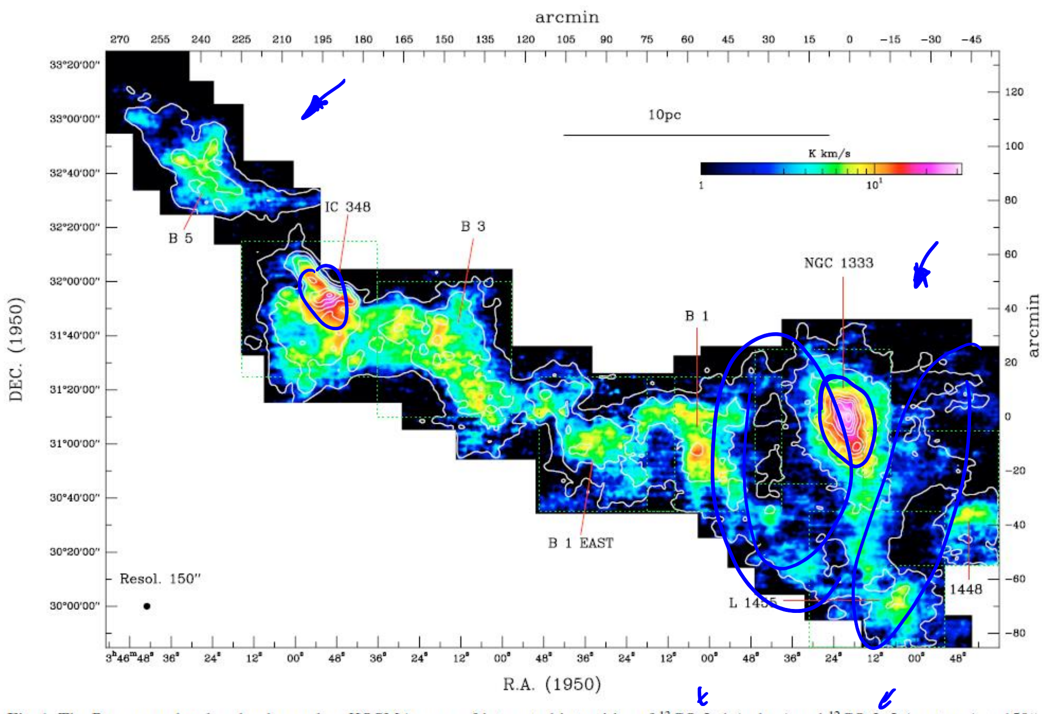
2.2 Internal Structure of GMCs

GMCs are not spheres

complex internal structure

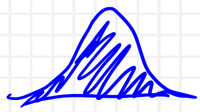
filamentary, clumpy, most mass in low n structures

$< n > \sim 100\ \mathrm{cm}^{-3}$, diameter few 10 pc

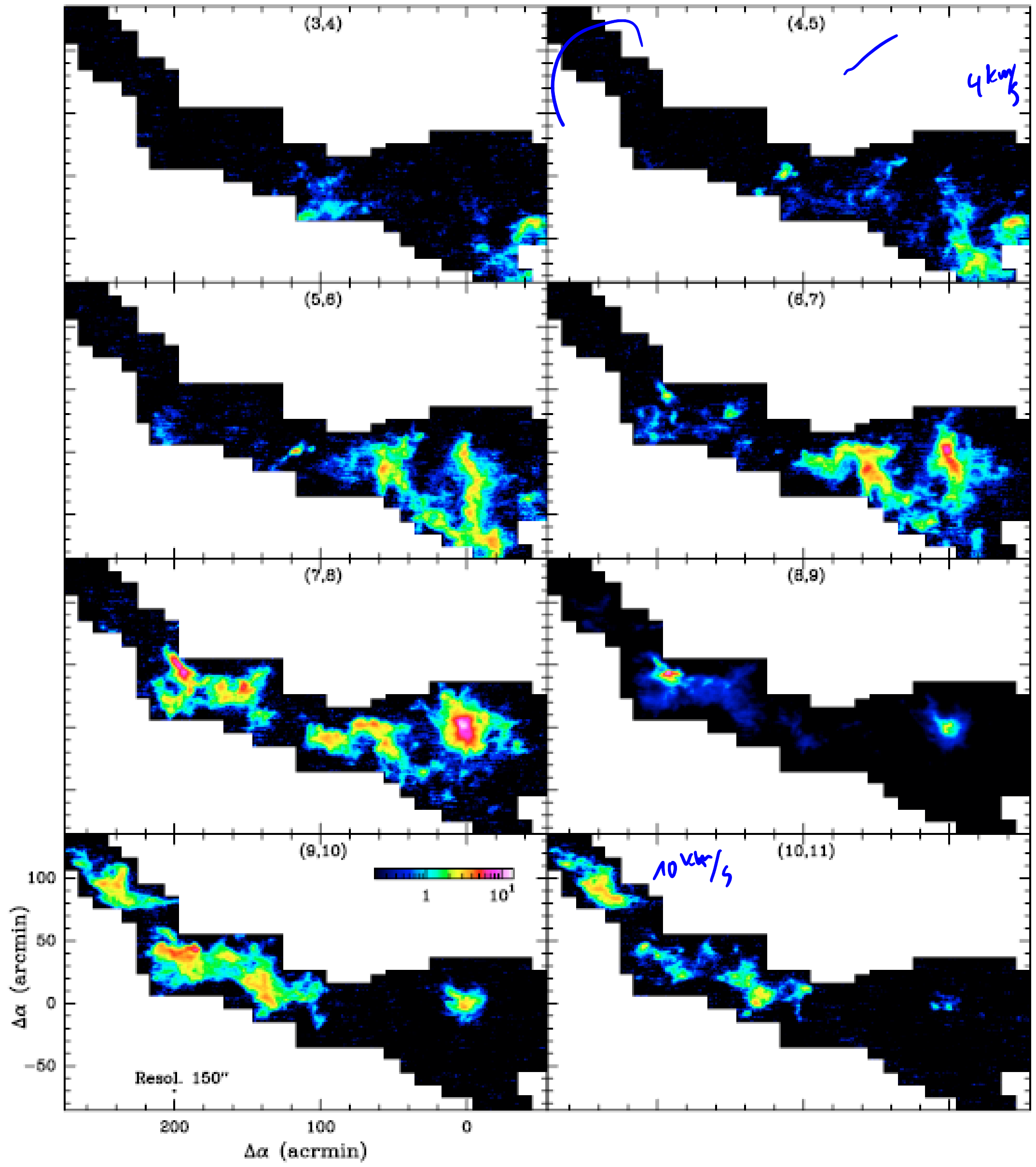


Sun et al. 2006

Fig. 1. The Perseus molecular cloud complex. KOSMA maps of integrated intensities of ^{13}CO 2–1 (colors) and ^{12}CO 3–2 (contours) at 150″ resolution. The integration interval is 0–16 km s^{-1}. Colors run from 1 K km s^{-1} (∼1σ) to 32 K km s^{-1}. Contours range from 6.6 K km s^{-1} (∼3σ) to 83 K km s^{-1} in steps of 9 K km s^{-1}. The (0, 0) position corresponds to RA = 03:26:00, Dec = +31:10:00 (B1950). Seven sub-regions are marked by dotted square boxes of 50′ × 50′.



3-4 km/s



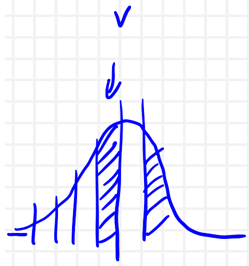


Fig. 3. ^{13}CO 2–1 velocity channel maps of the Perseus region. The velocity range runs from 3 km s^{-1} to 11 km s^{-1} with an interval of 1 km s^{-1} which is indicated on the top of each plot. The intensities are plotted from 0.7 K km s^{-1} ($\sim 1\sigma$) to 15 K km s^{-1}.

Sun et al. 2006

$\sigma \approx 8$ km/s

velocity structure is similarly complex

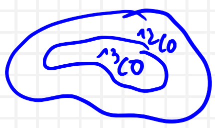
velocity distribution much wider than thermal sound speed ($c_s \sim 0.2 \text{ km s}^{-1}$)

MOVIE: NGC 1333 in 3D

from: A. Goodman's website:

https://www.cfa.harvard.edu/COMPLETE/astromed/

^{12}CO: traces less dense gas, ^{13}CO traces more dense gas

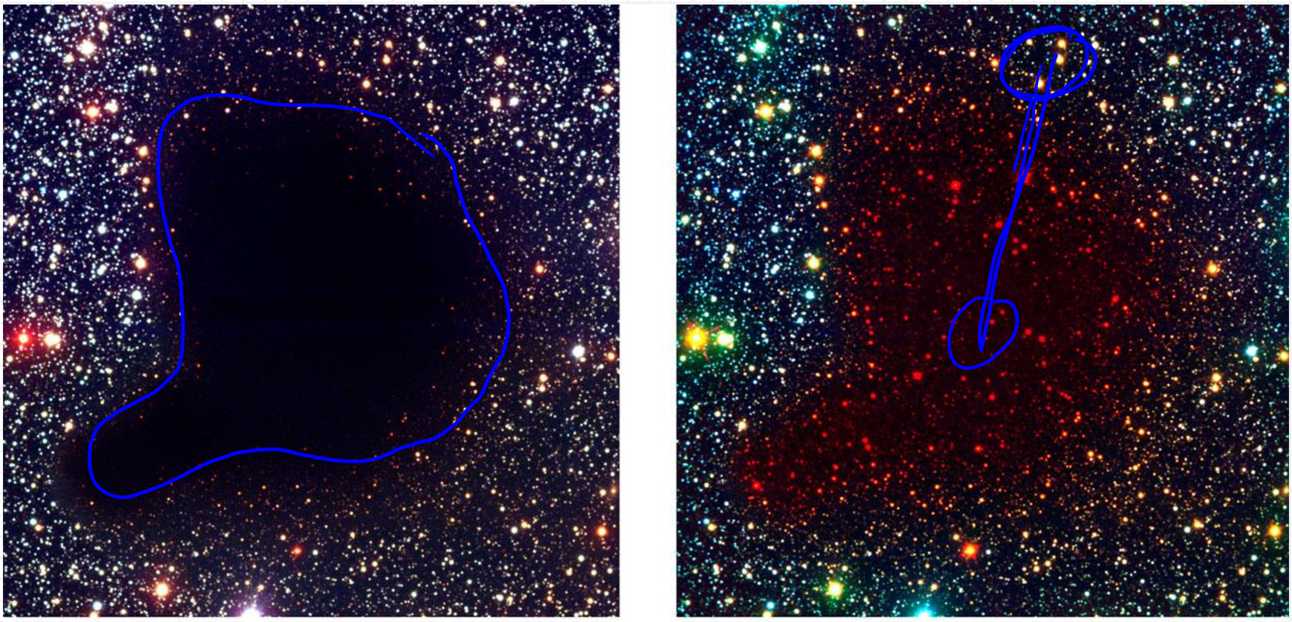


2.3 Cores

At smaller scales. $n \sim 10^5 - 10^7\,\mathrm{cm}^{-3}, M \sim \text{few } M_\odot$

spherical

=> cores progenitors of single stars or star systems



B, V, I B, I, K

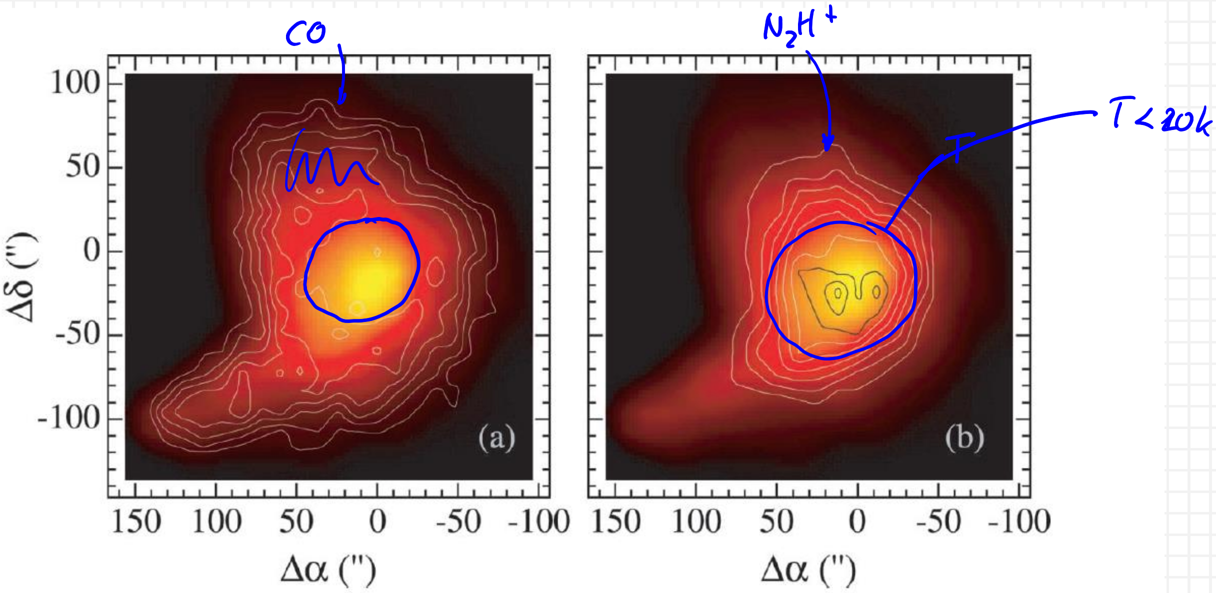


FIG. 1.—(*a*) Comparison of $C^{18}O$ $J = 1$–0 integrated emission (*contours*) in B68 superposed on a map of visual extinction derived by ALL01 and convolved to the IRAM resolution. The $C^{18}O$ contours begin at 0.2 K km s^{-1} and step in units of 0.1 K km s^{-1}. The A_V image is scaled from 0 to 27 mag. (*b*) Comparison of N_2H^+ $J = 1$–0 integrated emission (*contours*) and the visual extinction image. The N_2H^+ contours begin at 0.3 K km s^{-1} and step in units of 0.2 K km s^{-1}. These maps were referenced to $\alpha = 17^h22^m38.^s2$ and $\delta = -23°49'34.''0$ (J2000). The peak A_V is located 6'' east and 12'' south of this position.

Credit:ESO & (Bergin et al. 2002)

GMCs: highly supersonic ← non thermal

cores: subsonic (thermal broadening) ←

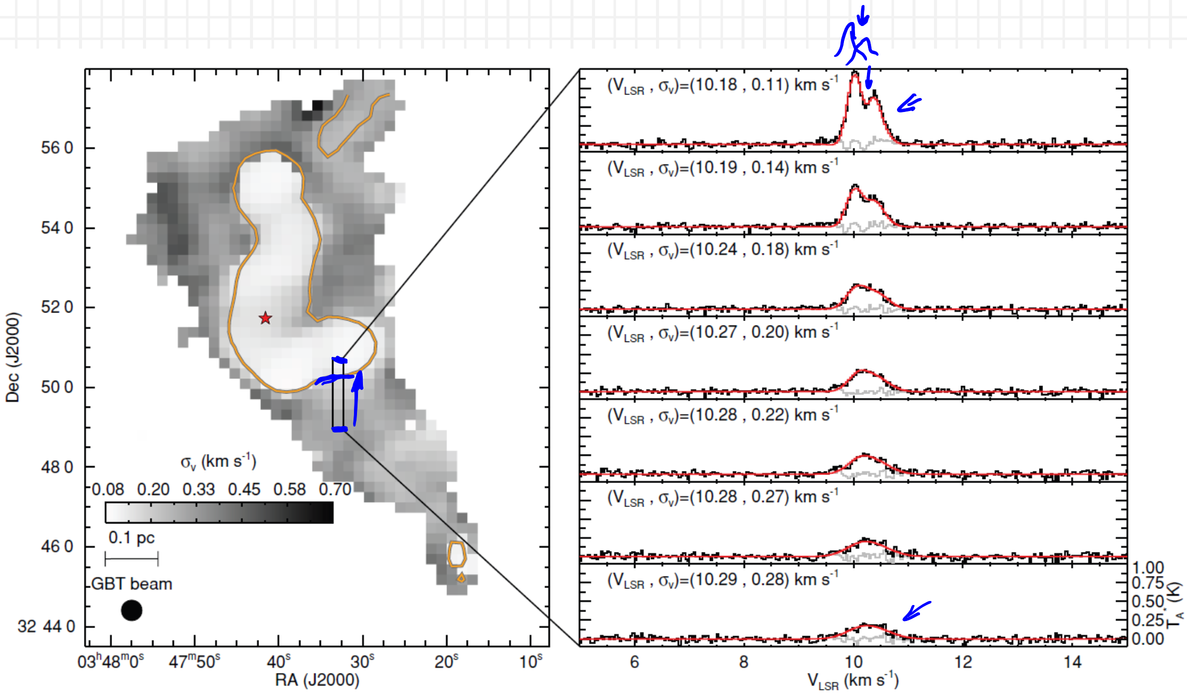


Figure 3. Velocity dispersion map derived from fitting all hyperfine components simultaneously. The protostar position is shown by the star, and the contour shows the contour $T_{peak} = 0.5$ K. The box on the map presents the region where we zoom in and present the corresponding spectra in the right panel, which shows only the main component of the $NH_3(1,1)$ line. The centroid velocity and velocity dispersion obtained from the fit are displayed for each position. Top spectra in the right panel display two main hyperfine components clearly separated thanks to their low-velocity dispersion (the coherent core), while when moving to positions outside the core the lines get weaker and broader (evident by the disappearance of the gap between hyperfine components).

(Pineda et al. 2010)