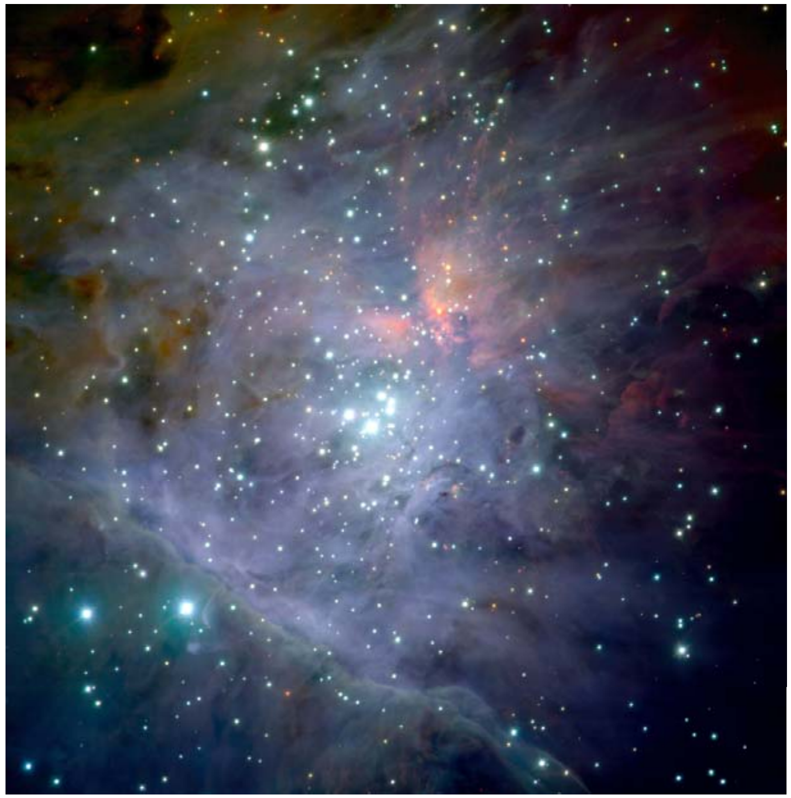
Part III

Early stages in stellar evolution



PhD course originally developed by René Liseau
Updated to Master level course by Alexis Brandeker

Part III

Early stages in stellar evolution

= star formation

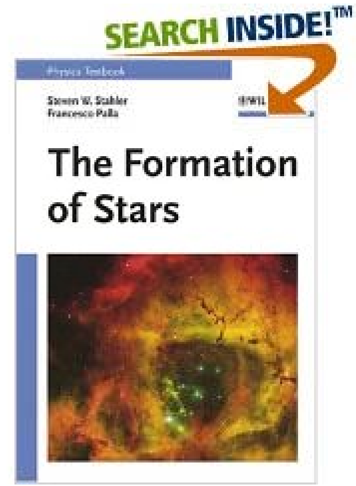
What will the course contain?

- Large topic; searching for papers with ”star formation” in the *title* on ADS returns **180793** results (as of 2008-05-17).
- This third part of the course stretches over 7 lectures × 90 min = **37800 s**. (However, 5 hp = 133 h = 480000 s!)
- Clearly we have to be selective.

Book of choice:

The Formation of Stars

by Stahler and Palla, 2004



Large brick, 850 pages! → Only subset will be covered.

- L15 – General Overview / Pre-collapse phase I
  Chapt. 1, 2, 4
- L16 – Pre-collapse phase II
  Chapt. 3, 4, 9
- L17 – Collapse phase I
  Chapt. 9, 10

Book of choice:

The Formation of Stars

by Stahler and Palla, 2004

- L18 – Collapse phase II
  Chapt. 9, 10
- L19 – Circumstellar disks I
  Chapt. 11, 17
- L20 – Pre-main-sequence evolution, multiplicity
  Chapt. 11, 12
- L21 – Circumstellar disks II – debris disks
  Chapt. 18

Homework / examination

3 problem sets with problems of varying degree of difficulty (for varying degree of grades!), to be handed in no later than

Friday, June 20, 24:00

for higher grade than pass (E).

Literature projects in star formation

- Suggestions handed out earlier.
- Please feel free to make your own suggestion!
- Only one student per topic; first come, first served.
- To be presented on

  Monday, June 16, 10:00–14:00.

Early stages in stellar evolution

- **L15 – General Overview / Pre-collapse phase I**
- L16 – Pre-collapse phase II
- L17 – Collapse phase I
- L18 – Collapse phase II
- L19 – Circumstellar disks I
- L20 – Pre-main-sequence evolution
- L21 – Circumstellar disks II – debris disks

How do we know that stars presently form?

ms lifetimes = nuclear times

Table 1.1 Properties of the Main Sequence

Mass ($M_\odot$)	Sp. Type	M_V (mag)	log L_{bol} ($L_\odot$)	log T_{eff} (K)	t_{MS} (yr)
60	O5	−5.7	5.90	4.65	3.4×10^6
40	O6	−5.5	5.62	4.61	4.3×10^6
20	O9	−4.5	4.99	4.52	8.1×10^6
18	B0	−4.0	4.72	4.49	1.2×10^7
10	B2	−2.4	3.76	4.34	2.6×10^7
8	B3	−1.6	3.28	4.27	3.3×10^7
6	B5	−1.2	2.92	4.19	6.1×10^7
4	B8	−0.2	2.26	4.08	1.6×10^8
2	A5	1.9	1.15	3.91	1.1×10^9
1.5	F2	3.6	0.46	3.84	2.7×10^9
1	G2	4.7	0.04	3.77	1.0×10^{10}
0.8	K0	6.5	−0.55	3.66	2.5×10^{10}
0.6	K7	8.6	−1.10	3.59	
0.4	M2	10.5	−1.78	3.54	
0.2	M5	12.2	−2.05	3.52	
0.1	M7	14.6	−2.60	3.46	

← $t_{\text{Trapezium cluster}}$ θ Ori

← t_{Sun}

← t_{BigBang}

$$t_{\text{nuc}} \propto Mc^2/L \propto M^{-\alpha}, \quad \alpha > 0$$

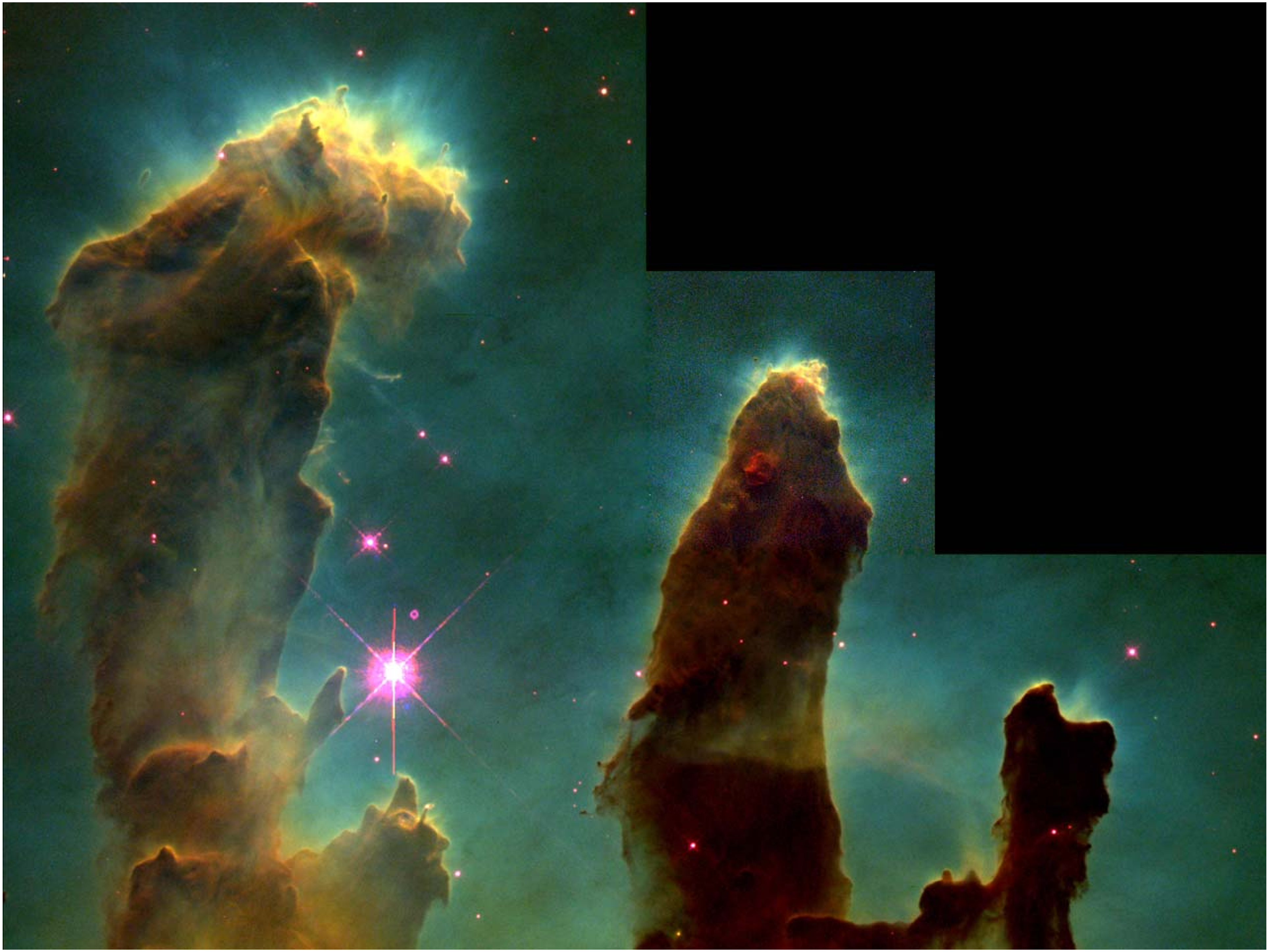
Relevant stellar evolution time scales:

dynamical $$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}} = 6\times10^{5}\left(\frac{M}{M_{\odot}}\right)^{-1/2}\left(\frac{R}{R_{\odot}}\right)^{3/2}\ \mathrm{yr}$$

<< thermal $$t_{\mathrm{KH}} = \frac{GM^{2}}{RL} = 3\times10^{7}\left(\frac{M}{M_{\odot}}\right)^{2}\left(\frac{R}{R_{\odot}}\right)^{-1}\left(\frac{L}{L_{\odot}}\right)^{-1}\ \mathrm{yr}$$

<< main sequence $$t_{\mathrm{nuc}} = \frac{\Delta Mc^{2}}{L} = 1\times10^{10}\left(\frac{M}{M_{\odot}}\right)\left(\frac{L}{L_{\odot}}\right)^{-1}\ \mathrm{yr}$$

Where do stars form?



What is the fraction of a galaxy's mass turned into stars, and locked there?

36 *2 The Interstellar Medium*

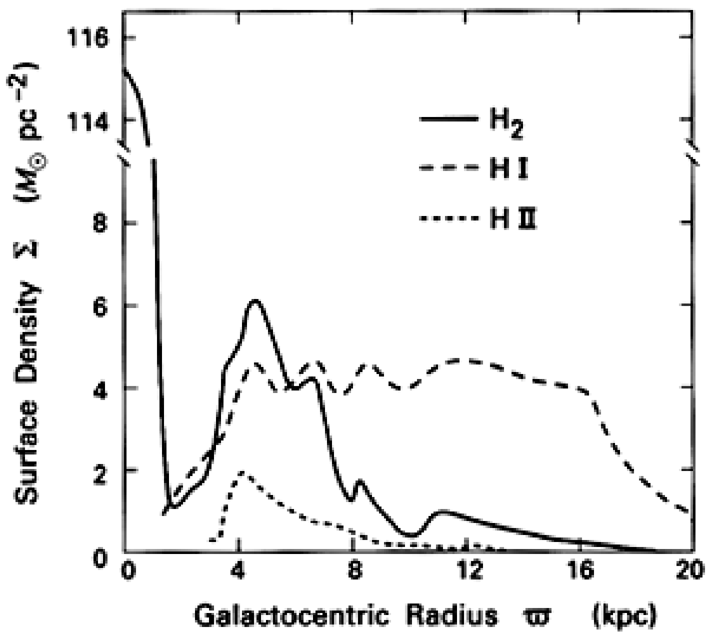


Figure 2.3 Galactic surface densities of H_2, HI, and HII gas. The densities are shown as a function of radial distance from the Galactic center. Note the high central peak of the molecular component. The ionized component shown is only that within HII regions.

Global concepts

(on galactic scales, in space and time)

IMF Initial Mass Function

$$n(M_{\rm star})dM_{\rm star} = \frac{N(M_{\rm star})dM_{\rm star}}{\int N dM_{\rm star}} \qquad D(\mathrm{IMF}) = 1$$

SFR Star Formation Rate

$$\dot{M} = \frac{\mathrm{d}M_{\rm stars}}{\mathrm{d}t} \qquad D(\mathrm{SFR}) = M_{\rm o}\,\mathrm{yr}^{-1}$$

SFE Star Formation Efficiency

$$\frac{M_{\rm stars}}{M_{\rm stars} + M_{\rm gas+dust}} \qquad D(\mathrm{SFE}) = 1 \ (\%)$$

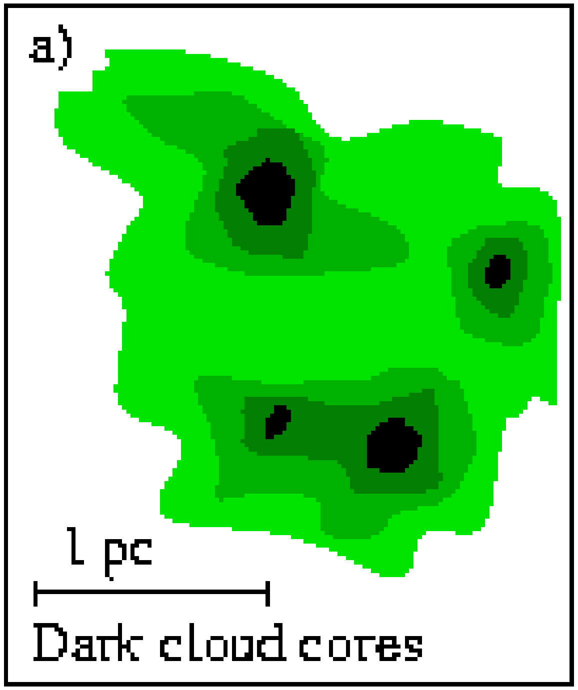
Local concepts

(on cloud scales, in space and time)

IMF   Initial Mass Function

SFR   Star Formation Rate

SFE   Star Formation Efficiency



In general

IMF Initial Mass Function

What Form ?

SFR Star Formation Rate

What Value ?

SFE Star Formation Efficiency

What Time Dependence ?

Pre-collapse phase:

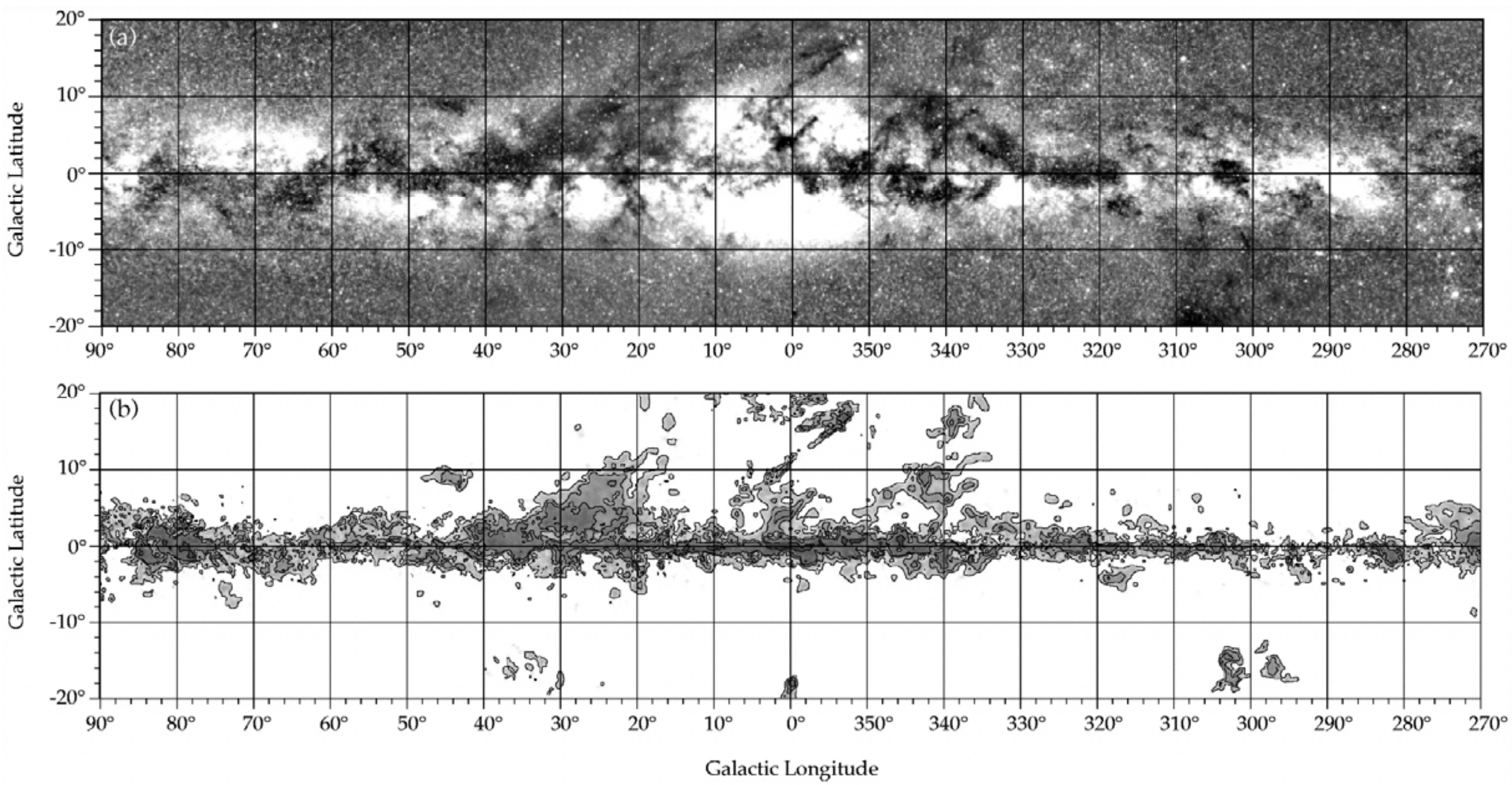
The clouds out of which stars form

Interstellar clouds

Historical milestones

1784	**Visual Eye (optical)**	**Herschel, in: *Construction of the Heavens: holes in the sky***
1918	**Imaging (optical)**	**Curtis, PASP 30, 65, *dark nebulae***
1937	**1st detection: CH (optical)**	**Swings & Rosenfeld, ApJ 86, 483**
1941	**1st detection: CH^+ (optical)**	**Douglas & Herzberg, ApJ 94, 381**
1951	**1st detection: H I (21 cm)**	**Ewen & Purcell, Nature 168, 356**
1963	**1st detection: OH (18 cm)**	**Weinreb et al., Nature 200, 829**
1965	**1st detection: CMB (7.3 mm)**	**Penzias & Wilson, ApJ 142, 419**
1970	**1st detection: CO (2.6 mm)**	**Wilson et al. , ApJ 161, L 43**
1983	**multimode: MIR – FIR**	**IRAS *sky survey***
1989	**multimode: NIR – mm**	**COBE *sky survey***
1995	**multimode: NIR – FIR**	**ISO *observatory***
2003	**multimode: MIR – FIR**	**Spitzer Space Telescope**
2009	**Multimode: FIR – submm**	**Herschel (again!) Space Observatory**

Interstellar *Molecular* clouds: Galactic distribution



Visual Obscuration

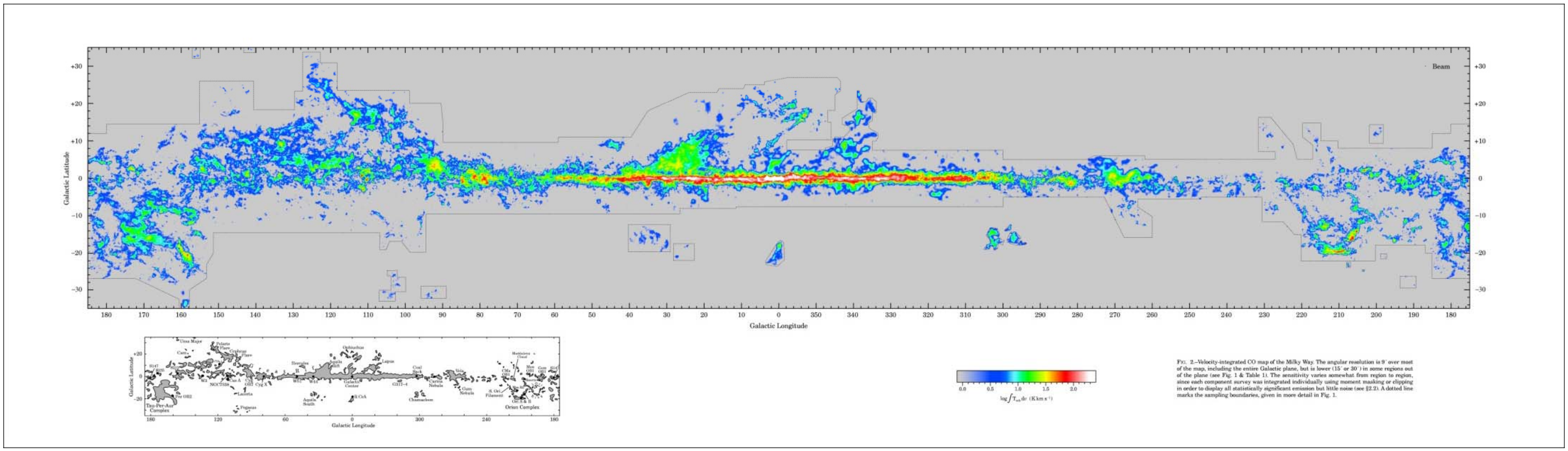
CO emission Distribution

cf. also H I
IRAS 100 μm
et c

CO (J = 1-0) Integrated Line Intensity

Dame, Hartmann & Thaddeus, 2001, ApJ 547, 792

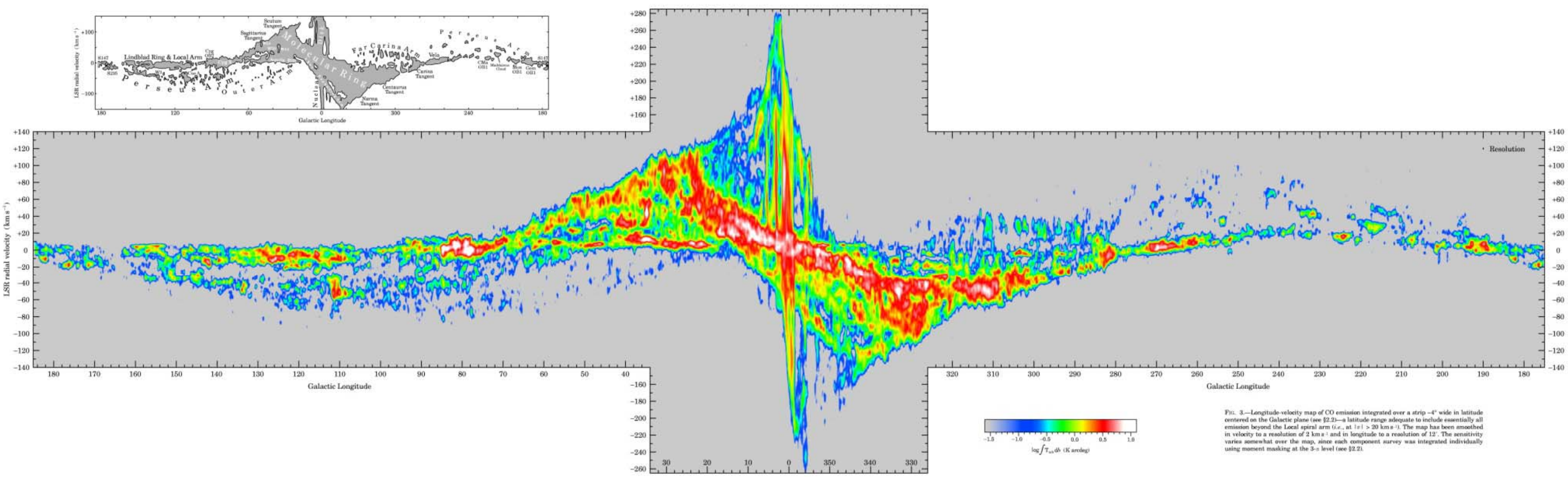
Interstellar *Molecular* clouds: Galactic distribution



CO (J = 1-0)   Integrated Line Intensity (K km s^{-1})

Dame, Hartmann & Thaddeus, 2001, ApJ 547, 792

Interstellar *Molecular* clouds: Galactic distribution

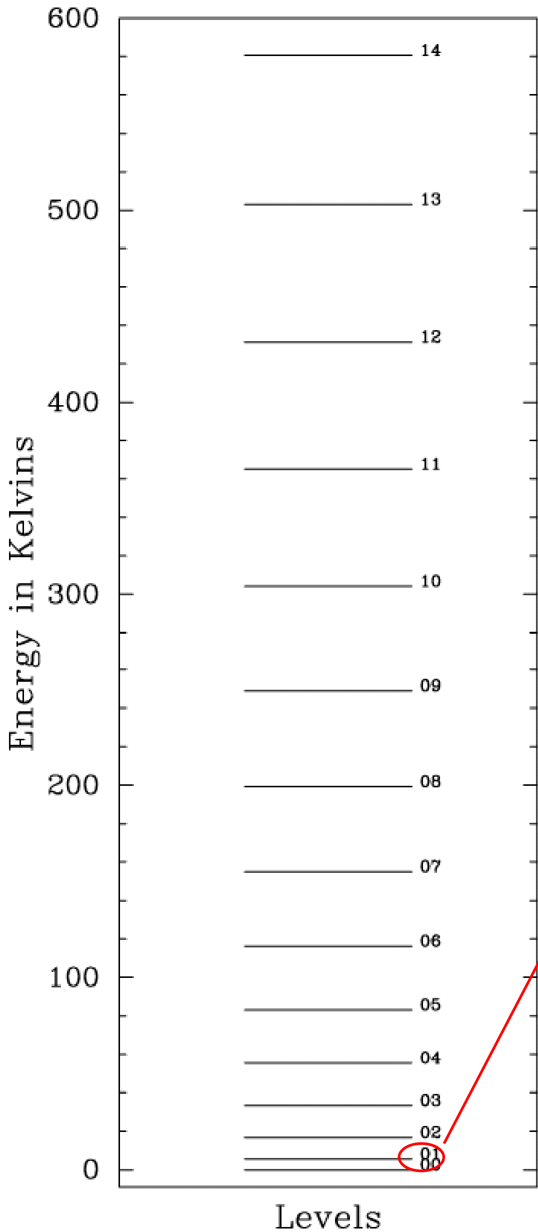


CO (J = 1-0) Radial velocity (LSR)

Dame, Hartmann & Thaddeus, 2001, ApJ 547, 792

CO

B(rot): 57.63597 GHz   De = 1.8357E−04 GHz   Dipole Mom = 0.112 Debye

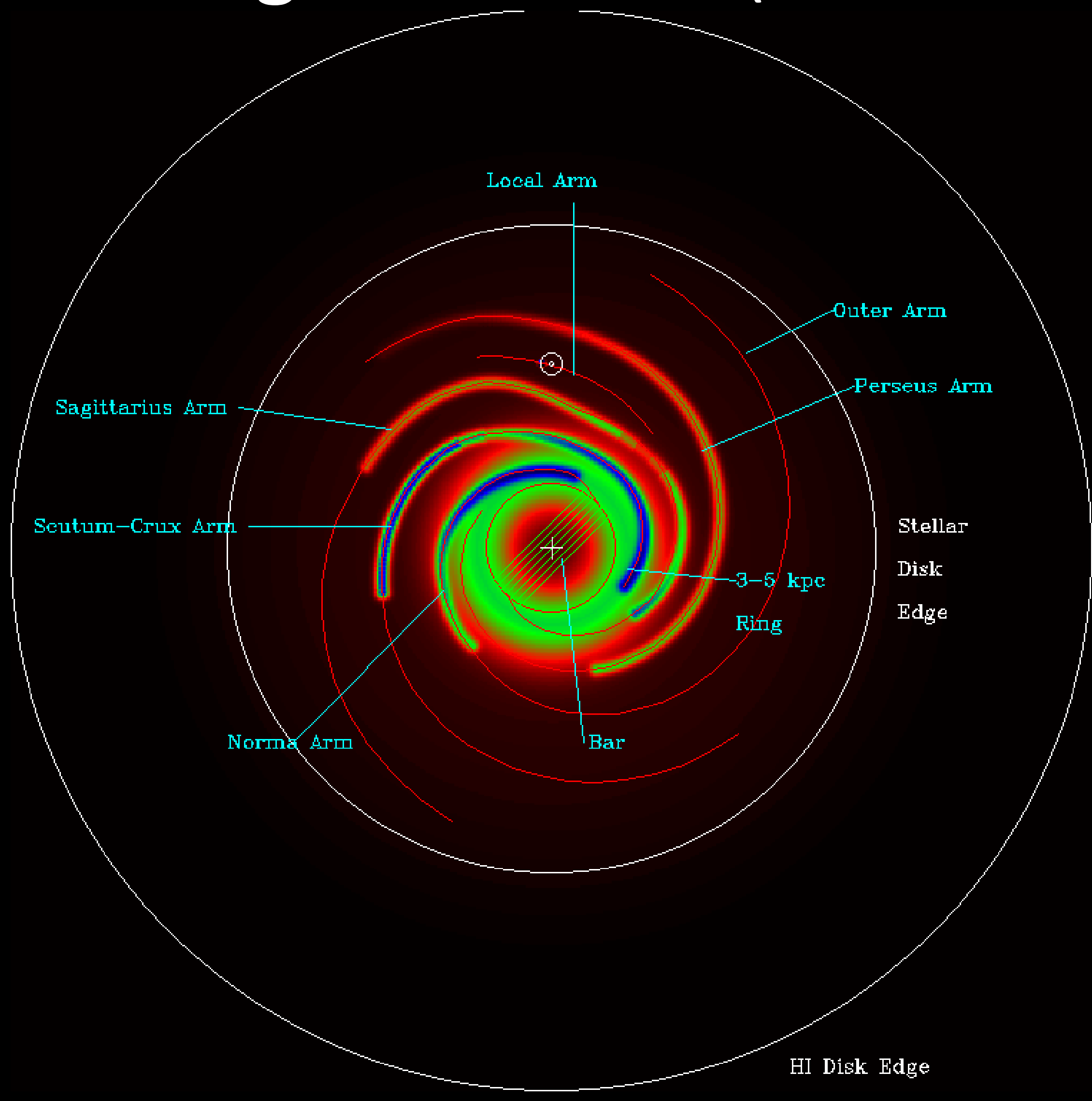


Quantum Numbers J K K1	Level Degeneracy	Energy Above Ground (Kelvins)
00	1.	0.00
01	3.	5.53
02	5.	16.60
03	7.	33.19
04	9.	55.32
05	11.	82.97
06	13.	116.16
07	15.	154.87
08	17.	199.11
09	19.	248.87
10	21.	304.16
11	23.	364.97
12	25.	431.29
13	27.	503.13
14	29.	580.49

E_{up}/k_B = 5.5 K

QN(up) J K K1	QN(low) J K K1	Freq (GHz)	A(U−L)	B(L−U)	Log(Tau) relative
01	00	115.271	7.45E−08	9.90E+06	0.08
02	01	230.538	7.16E−07	6.60E+06	0.62
03	02	345.796	2.59E−06	5.94E+06	0.87
04	03	461.041	6.36E−06	5.66E+06	0.98
05	04	576.268	1.27E−05	5.50E+06	1.00
06	05	691.473	2.23E−05	5.40E+06	0.94
07	06	806.652	3.58E−05	5.33E+06	0.82
08	07	921.800	5.38E−05	5.28E+06	0.63
09	08	1036.912	7.71E−05	5.24E+06	0.40
10	09	1151.985	1.06E−04	5.21E+06	0.11
11	10	1267.014	1.42E−04	5.19E+06	−0.22
12	11	1381.994	1.85E−04	5.17E+06	−0.60
13	12	1496.923	2.36E−04	5.15E+06	−1.03
14	13	1611.791	2.95E−04	5.13E+06	−1.50

Interstellar *Molecular* clouds: Solar neighbourhood (within 1 kpc)



Interstellar *Molecular* clouds: Solar neighbourhood (within 1 kpc)

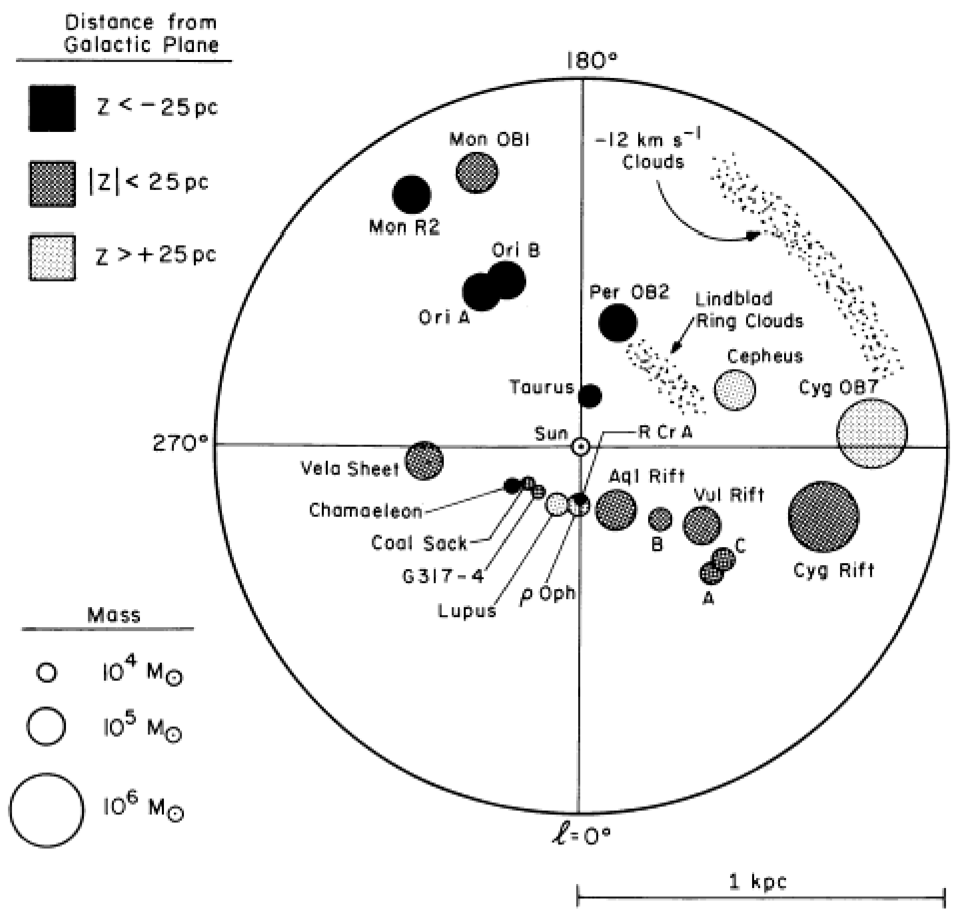


FIG. 7.—The distribution in the Galactic plane of molecular clouds within 1 kpc of the Sun (Table 2). The circle radii are proportional to the cube roots of the cloud masses and in most cases are close to the clouds' actual radii. The shading indicates distance from the Galactic plane.

The general regions of the " -12 km/s " and Lindblad Ring clouds are indicated but individual clouds are not shown. The widths of these regions in heliocentric distance are unknown; the widths shown are arbitrary.

Interstellar *Molecular* clouds: Solar neighbourhood (within 1 kpc)

Scale Height, H	75 pc
Molecular Mass, M	$4\ 10^6\ M_o$
Surface Density, Σ	$1\ M_o\ \mathrm{pc}^{-2}$
Mass Density, $\rho(z_0)$	$7\ 10^{-3}\ M_o\ \mathrm{pc}^{-3}$
Particle Density, $n(z_0)$	$0.1\ H_2\ \mathrm{cm}^{-3}$

Interstellar *Molecular* clouds: Individual clouds (solar neighbourhood)

Type	***R*** **(pc)**	*n* (cm^{-3})	*M* (M_o)	Δv ($km\ s^{-1}$)	*T* (K)	Cores and Stars
Diffuse	0.3 – 3	30 – 500	0.5 – 100	0.7 – 1.5	10 ?	**Low-mass**
Dark	3 – 10	10^{2-3}	10^{3-4}	1 – 3	10	**Low-mass**
Giant	20 – 100	10 – 300	10^{5-6}	5 – 15	10–20	**Massive and Low-mass**
Average	***Property***	***Depends***	***On***	***Molecular***	***Tracer***	***?***

is there a potential problem?

CO (J = 1- 0)

Myers 1991, in: *Molecular Clouds*, James & Millar (eds.), p. 1

Interstellar *Molecular* clouds: Individual clouds (solar neighbourhood)

Type	R (pc)	n (cm^{-3})	M (M_o)	Δv (km s^{-1})	T (K)	Cores and Stars
Low-Mass	**0.05 – 0.2**	10^{4-5}	**0.3 – 10**	**0.2 – 0.4**	**10**	**T Tauri**
Massive...						
Large	**0.3 – 0.6**	10^{4-5}	**30 - 10^4**	**1 – 2**	**10 – 30**	**OB**
Small	**0.01– 0.03**	10^{6-7}	**0.3 – 300**	**1 – 3**	**30 – 100**	**OB**

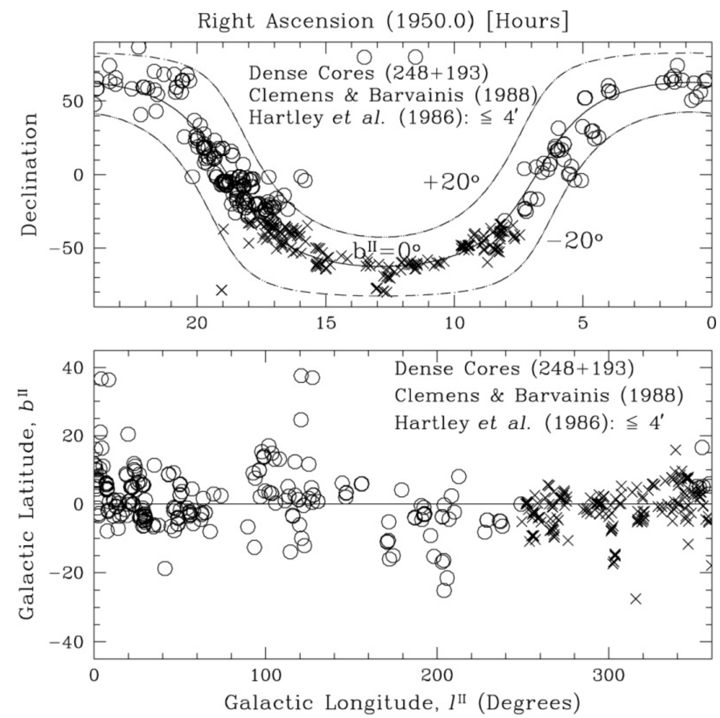
NH_3 (J,K = 1,1)

Myers 1991, in: *Molecular Clouds*, James & Millar (eds.), p. 1

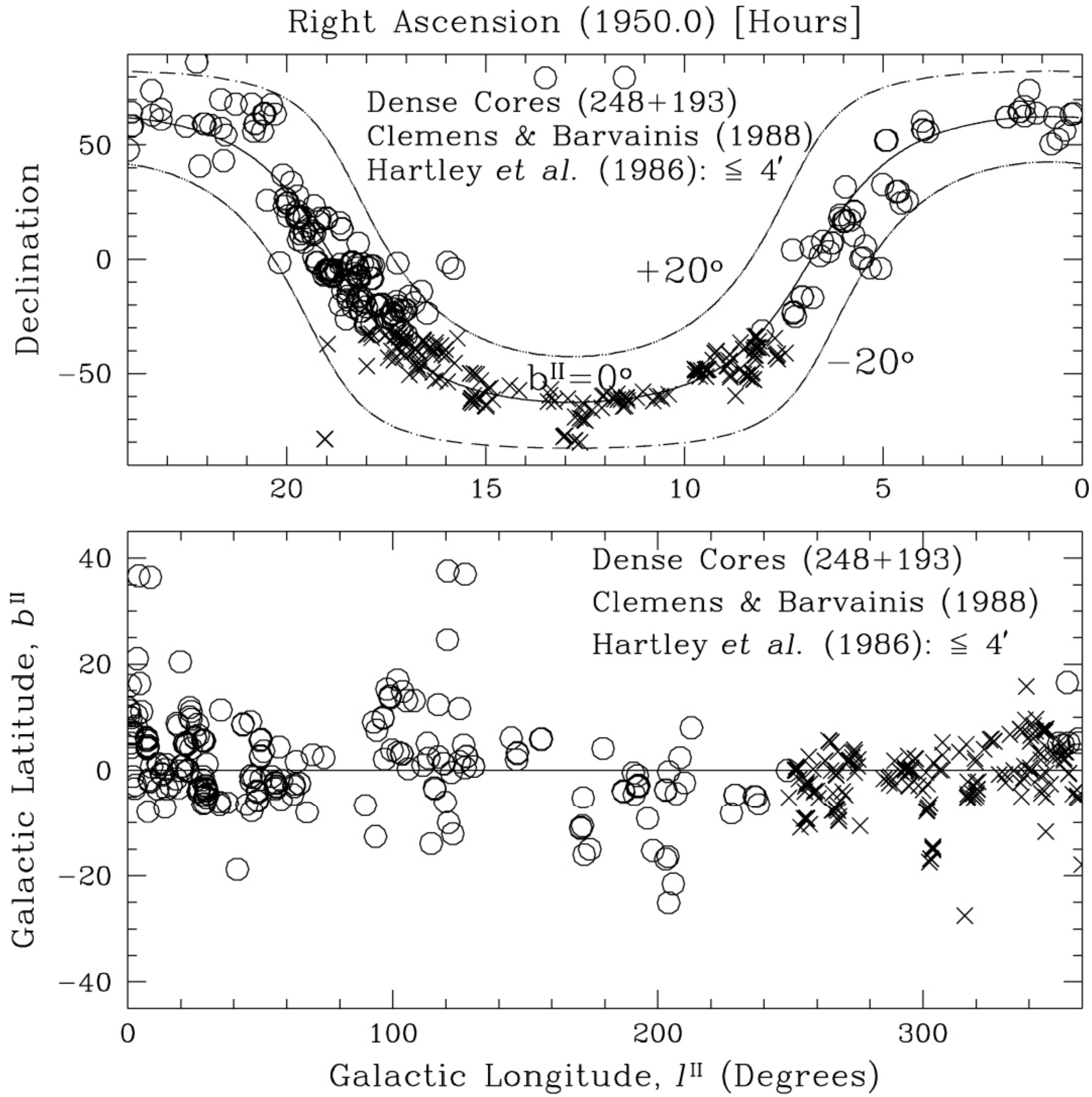
Interstellar *Dark* clouds and cores

Barnard 1927, Univ. Chicago Press — *Catalogue of 349 dark objects in the sky*
Bok & Reilly 1947, ApJ 105, 255 — G*lobules* size = 5 arcsec to 60 arcsec
Lynds 1962, ApJS 7, 1 — *DC*s 1802 north of $\delta = -33^o$
Hartley et al. 1986, AAS 63, 27 — *DC*s 1101 south of $\delta = -33^o$
Clemens & Barvainis, 1988, ApJS 68, 257 <10´ 248 north of $\delta = -33^o$

observational selection effects ?



Off the galactic plane few background stars



Interstellar *Dark* clouds and cores

Optical selection based on *optical obscuration = extinction*

Empirically (Bohlin, Savage & Drake 1978, ApJ 224, 132):

$N(\mathrm{H\,I} + 2\mathrm{H_2}) = 1.9 \times 10^{21}\ A_\mathrm{V}\ \mathrm{cm}^{-2}$

where the extinction by dust in magnitudes

$A_\mathrm{V} = 2.5 \times {}^{10}\log e \times \tau_\mathrm{V}$

or, in general,

$A_\lambda = 1.086\,\tau_\lambda \approx \tau_\lambda$

$\Rightarrow$

what is $A(\lambda)$? (``extinction curve´´)

most widely used is (0.3 to 10 µm)

Rieke & Lebofsky (1985, ApJ 288, 618): $A_\mathrm{V}/E(\mathrm{B-V}) = 3.09$

is fit within $0.55 \le \lambda \le 2.2\ \mu\mathrm{m}$ to better than 0.5% by

$A_\lambda / A_\mathrm{V} = 3.0134 - 5.621\lambda + 4.3847\lambda^2 - 1.539\lambda^3 + 0.2181\lambda^4$

Interstellar *Dark* clouds and cores

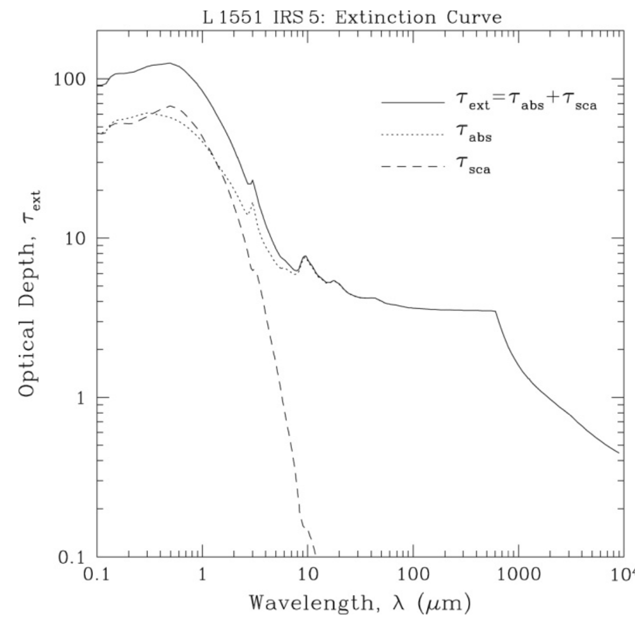
Optical selection based on *optical obscuration*

$$A_\lambda = 2.5 \log e \times \tau_\lambda = 1.086\, \tau_\lambda$$

i.e. $A_\lambda \approx \tau_\lambda$

so what is $A(\lambda)$?

Dependence on what physics ?
Rieke & Lebofsky curve applicable where ?
Is $A(\lambda)$ a function of the time, i.e. $A(\lambda, t)$?



Example:

White et al. 2000, AA 364, 741

Interstellar *Dark* clouds and cores

$\lambda = 0.55\ \mu m$

$A_V > 100$ mag ! ! !

Optical photographic plates
& CCD images: $A_V << 100^m$

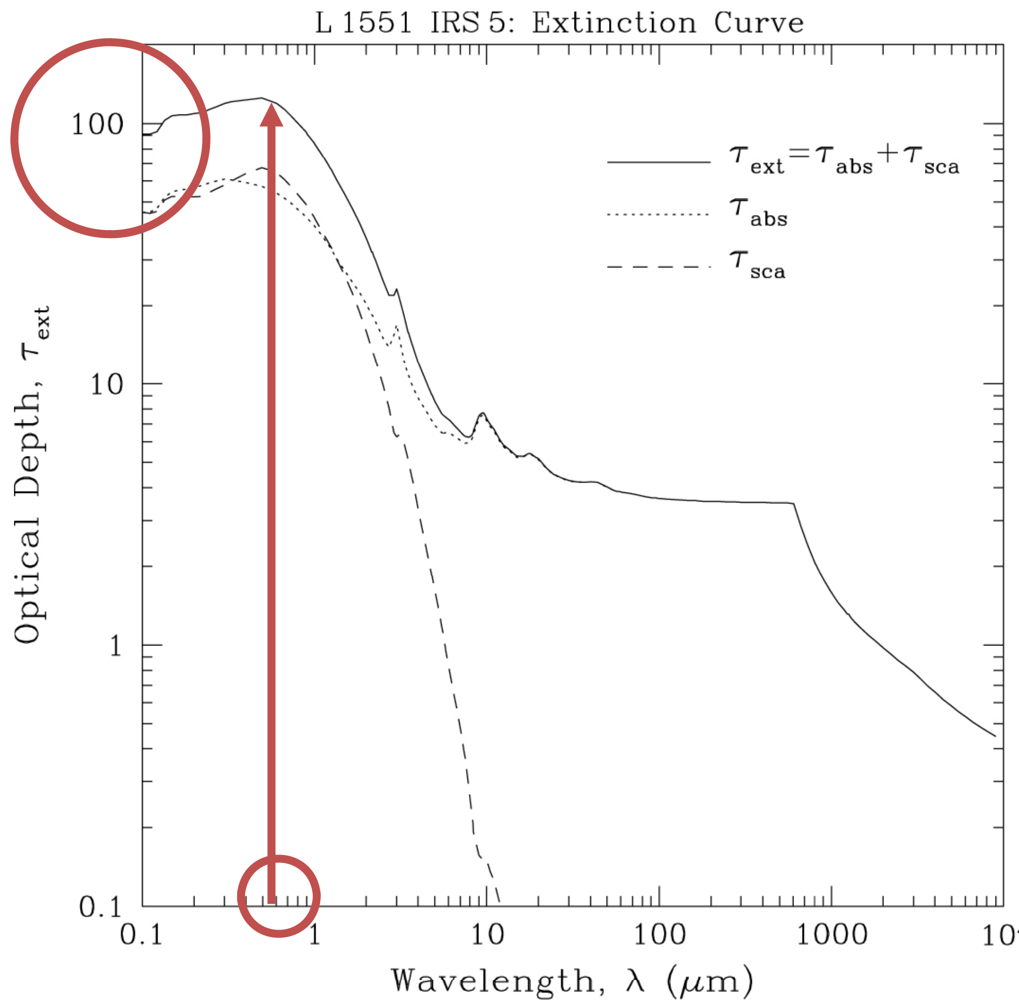
$N(H) \sim A_V$ saturation
$N(H) \sim A_V$ calibration ?

gas mass vs dust mass

``normal´´ $m_g/m_d = 100$

How well established ?

How relate A_V and $N(H_2)$?



White et al. 2000, AA 364, 741

Interstellar *Dark* clouds and cores

Molecular line observations

Benson & Myers 1989, APJS 71, 89	119 Barnard/Lynds objects	NH_3 (1,1)
Clemens et al. 1991, APJS 75, 877	248 Clemens/Barvainis cores	CO (2-1)
Bourke et al. 1995, MNRAS 276, 1067	169 Hartley et al. cores	NH_3 (1,1), (2,2)
Lemme et al. 1996, AA 312, 585	237 Clemens/Barvainis	NH_3 (1,1), (2,2)

Dust continuum observations

Launhardt & Henning 1997, AA 326, 329	59	CB	1.3 mm
Osterloh et al. 1997, ApJS 110, 710	31	CB	1.3 mm
Shirley et al. 2000, ApJS 131, 249	21	L & CB	450 μm & 850 μm
Visser et al. 2001, AJ 124, 2756	42	CB & L	850 μm

In extragalactic applications, one uses CO and

$$N(\mathrm{H_2}) = X_{\mathrm{CO}} \int T_{\mathrm{R}} \mathrm{d}V$$

where

$$X_{\mathrm{CO}} = (1-5)\times 10^{20}\ \ \mathrm{cm^{-2}} /(\mathrm{K\ km\ s^{-1}})$$

is the Conversion Factor

Interstellar *Dark* clouds and cores

More observational results:

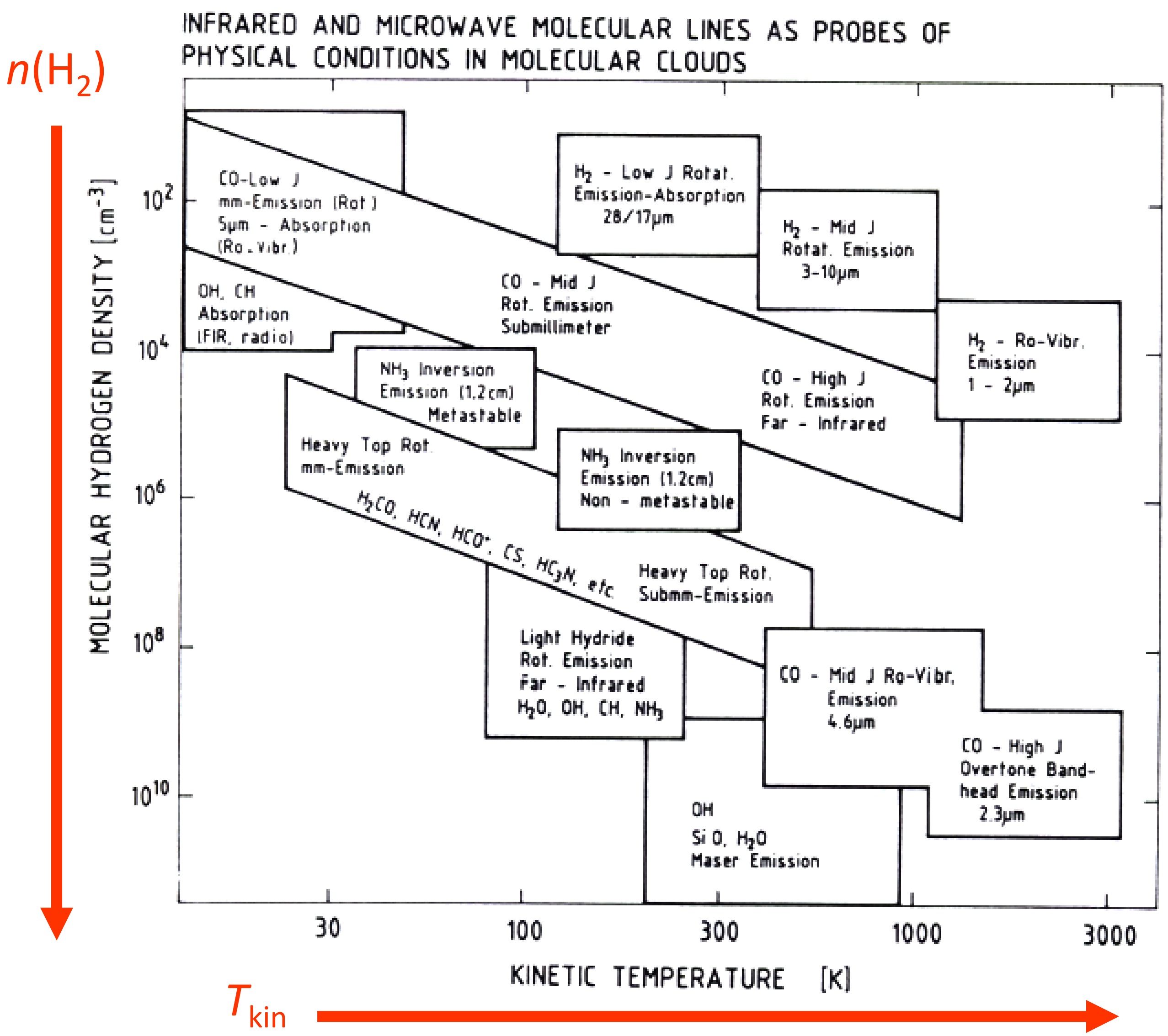
Mean aspect ratio ~ 2, but prolate? oblate?

> 50% of cores have IRAS source

no difference globules / embedded cores

Core with IRAS source	***without IRAS source***
broader lines	**narrow / thermal widths**
larger size	**smaller**
more evolved ?	**younger ?**

Molecular Probes of T_{kin} and $n(H_2)$



Genzel 1990, in: *The Physics of Star Formation and Early Stellar Evolution*, Lada & Kylafis (eds.), NATO ASI 342, p.155 - 219

T_{kin}

$n(H_2)$

Table III. Temperature and density probes in molecular clouds

METHOD	STRENGTH	WEAKNESS
Temperature		
Brightness of optically thick mm-lines (e.g., ^{12}CO 1→0: $T_R = T_{ex} \sim T_{kin}$)	easy to measure	filling factor of emission $\Phi_{AL} < 1$ (eq. 8) and method may underestimate T_{kin}
Level population as a function of energy from metastable NH_3 inversion lines at ~ 1.2 cm (also other symmetric tops, such as CH_3CN, CH_3C_2H)	many energy levels available at about the same wavelength	optical depth and density correction not easy, only applicable to dense regions where NH_3, CH_3CN etc. are abundant
Level population as a function of energy from rotational lines of molecules in mm/submm (emission, e.g., CO)	very sensitive for $E_{ul} > kT_{kin}$ (eq. 18), gives also density information	laborious measurements need to be made at very different wavelengths, must solve the entire excitation problem (eq. 26) and take into account optical depth effects
.... from ro-vibrational lines in near-IR (absorption)	same as above, many energy levels at about the same wavelength	only line of sight toward bright continuum sources
Density		
Average volume density from column density and cloud size (e.g., ^{13}CO or $C^{18}O$)	easy to measure	underestimes local densities as volume filling factors ≪ 1 (clumpiness), strongly depends on abundances and T_{ex}
Detection of "density tracers", such as mm-lines of CS, HCN with *high* n_{crit}	easy to measure	rough first order indication, depends strongly on optical depth (trapping, eq. 34)
Measurement of non-metastable NH_3 inversion lines at 1.2 cm	many energy levels available at about the same wavelength	optical depth effects and FIR radiative pumping need to be taken into account
Level population as a function of energy from rotational lines above n_{crit} (subthermal regime), especially for optically thin species ($C^{18}O$, $H^{13}CN$, $C^{34}S$ etc.)	very sensitive to $n(H_2)$, gives also temperature information	laborious measurements need to be made at very different wavelengths, cross sections for all molecules but CO uncertain, must solve the entire excitation problem (eq. 26)

Genzel 1990, in: *The Physics of Star Formation and Early Stellar Evolution*, Lada & Kylafis (eds.), NATO ASI 342, p.155 - 219

Interstellar *Dark* clouds and cores
Rotation

Cloud	**d*v*/d*r*** (km s^{-1} pc^{-1})	***j**** (km s^{-1} pc)	**Reference**
Rosette	**0.18**	**47**	**Blitz & Thaddeus 1980**
Mon R 1	**0.20**	**45**	**Blitz 1978**
W 3	**0.30**	**27**	**Thronson et al. 1985**
Orion	**0.10**	**74**	**Kutner et al. 1977**
typical GMC	**< 0.05**	**<15**	**various; Blitz 1980**
typical DC	**1.5**	**3×10^{-3}**	**Goodman et al. 1993**

* for $q = 0.5$ and $j = J/M = q R^2 \Omega$

j(sol sys) = 5 10^{-7} km s^{-1} pc

Interstellar *Dark* clouds and cores

Magnetic fields – spectral lines

Region	*Method*	B_{obs} (μG)
Intercloud Medium	Faraday rotation	5
Diffuse Cloud	Zeeman H I	7
Dark Cloud	Zeeman H I	5 – 10
	Zeeman OH	20 – 30
GMC	Zeeman H I	10
Massive Core	Zeeman OH	$100 – 10^3$
Maser Spots	Zeeman H_2O	10^4

Table adapted from Myers 1991

Interstellar *Dark* clouds and cores

Zeeman OH 18 cm *
Bourke et al. 2001, ApJ 554, 916

Zeeman OH 18 cm *
Crutcher 1999, ApJ 520,706

* 1665, 1667 MHz

TABLE 3

Molecular Cloud Analysis

Name (1)	B_{los} (μG) (2)	Log B (μG) (3)	Log N [$N(H_2)$ cm^{-1}] (4)	$(\Phi/M)_n$ (Sphere) (5)	$(\Phi/M)_n$ (Sheet) (6)
		Parkes			
RCW 38	38	1.58	21.97	0.8	1.6
RCW 57 (v2)[a]	203	2.31	22.04	3.7	7.3
Carina MC	<30	<1.48	21.82	<0.9	<1.8
Cham I	<12	<1.08	21.89	<0.3	<0.6
RCW 57 (v1)[a]	<12	<1.08	22.29	<0.1	<0.2
G326.7+0.6 (v1)[b]	<42	<1.62	22.08	<0.7	<1.4
G326.7+0.6 (v2)[b]	<13	<1.11	21.58	<0.7	<1.4
G327.3−0.5	<30	<1.48	22.45	<0.2	<0.4
G343.4−0.0	<9	<0.95	21.73	<0.3	<0.7
NGC 6334 (v1)[c]	<12	<1.08	22.25	<0.1	<0.3
NGC 6334 (v2)[c]	<12	<1.08	21.46	<0.8	<1.6
G8.1+0.2	<36	<1.56	22.56	<0.2	<0.4
		Green Bank			
W7	<18	<1.26	21.50	<1.1	<2.3
NGC 2264 IRS 2	<48	<1.68	21.73	<1.8	<3.5
G14.0−0.6	<56	<1.75	22.15	<0.8	<1.6
IRAS 18153−1651	<51	<1.71	22.10	<0.8	<1.6
G14.5−0.6	<54	<1.73	22.22	<0.7	<1.3
IRAS 18164−1645	<51	<1.71	22.08	<0.9	<1.7
G20.8−0.1	<69	<1.84	21.09	<11.2	<22.1
G29.9+0.0	<78	<1.89	21.33	<7.0	<14.0
G78.5+1.2	<30	<1.48	21.59	<1.5	<3.0
G80.9−0.2	<27	<1.43	21.89	<0.7	<1.4
		Crutcher 1999			
W3 OH	3100	3.49	23.7	1.2	2.4
DR 21 OH1	710	2.85	23.6	0.4	0.7
Sgr B2	480	2.68	23.4	0.4	0.8
M17 SW	450	2.65	23.1	0.7	1.4
W3 (main)	400	2.60	23.2	0.5	1.0
S106	400	2.60	22.8	1.3	2.5
DR 21 OH2	360	2.56	23.3	0.4	0.7
OMC-1	360	2.56	23.2	0.5	0.9
NGC 2024	87	1.9	22.9	0.2	0.4
S88B	69	1.84	22.3	0.7	1.4
B1	27	1.43	21.9	0.7	1.3
W49B	21	1.32	21.6	1.1	2.1
W22	18	1.26	22.2	0.2	0.5
W40	14	1.15	22.	0.3	0.6
ρ Oph 1	10	1.	21.7	0.4	0.8
L1544[d]	11	1.04	22.3	0.1	0.2
NGC 6334[e]	150	2.18	22.7	0.6	1.2
OMC-N4[f]	<300	<2.48	23.1	<0.5	<0.9
Tau G[f]	<7	<0.85	21.6	<0.4	<0.7
L183[f]	<15	<1.18	21.2	<1.9	<3.7
L1647[f]	<11	<1.04	22.1	<0.2	<0.3
ρ Oph 2[f]	<13	<1.11	21.6	<0.7	<1.3
TMC-1[f]	<12	<1.08	21.9	<0.3	<0.6
L1495W[f]	<9	<0.95	21.6	<0.5	<0.9
L134[f]	<10	<1	21.3	<1.0	<2.0
TMC-1C[f]	<9	<0.95	21.9	<0.2	<0.5
L1521[f]	<9	<0.95	21.7	<0.4	<0.7
L889[f]	<6	<0.78	22.	<0.1	<0.2
Tau 16[f]	<7	<0.85	21.7	<0.3	<0.6

[a] $(v1) = -26.1$ km s^{-1} component, $(v2) = -22.6$ km s^{-1}.
[b] $(v1) = -44.8$ km s^{-1} component, $(v2) = -21.6$ km s^{-1}.
[c] $(v1) = -3.8$ km s^{-1} component, $(v2) = 6.3$ km s^{-1}.
[d] From Crutcher & Troland 2000.
[e] From Sarma et al. 2000. Corresponds to our NGC 6334 $(v1)$.
[f] Note that the values listed here for B_{los} are $3\sigma_B$ for consistency with our other results, rather than $B_{los} + 3\,\sigma$ as in Crutcher 1999.

Interstellar *Dark* clouds and cores

Magnetic fields – continuum

e.g., 800 μm map of
linear polarisation

see also:

Ward-Thompson et al. 2000, ApJ 537, L 135 3 L

Wolf et al. 2003, ApJ 592, 233 3 CB (+3 CB)

also give *B*-field strength: 257 μG

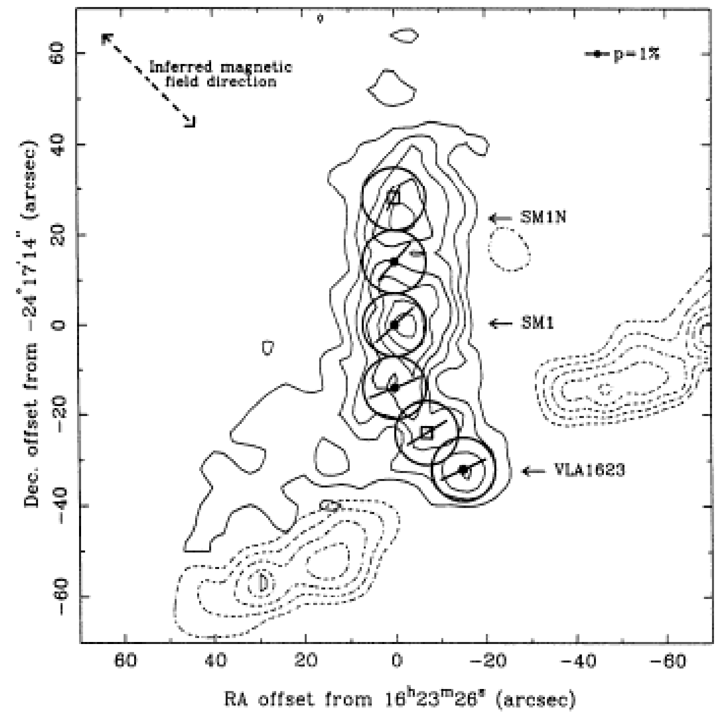


Fig. 2. 800 μm map of ρ Oph A region (from AWB), with a base contour level of 1.75 Jy/beam and equally-spaced intervals of 0.75 Jy/beam. Overlaid on top of the map are circles representing the 13.5″ FWHM beam size, within which are the measured 800 μm polarization vectors (the three northern-most points are from GMH). A 1 % polarization vector is shown for scaling purposes. An open square box indicates data which has a polarization signal-to-noise of ≤ 2.5. Also shown on the plot are the CO(2-1) outflow data (from André et al. 1990). Both the red-shifted and blue shifted lobes (respectively NW of VLA 1623, with radial velocity interval $12 \leq v \leq 18$ km/s, and SE, $-10 \leq v \leq -4$ km/s) have contours starting at 3 K km/s, with intervals of 1 K km/s. The heavy dashed line represents the average direction of the inferred magnetic field throughout the cloud.

Interstellar *Dark* clouds and cores

Time scales – ages

The `dynamical´ time scale

$$t_{\text{dyn}} \approx \frac{R_{\text{pc}}}{v_{\text{km s}^{-1}}} \text{ Myr}$$

cross communication (δP)
at the signal speed c_s

The isothermal sound speed

$$c_s = \left(\frac{\partial P}{\partial \rho}\right)^{1/2} \approx \left(\frac{\Gamma\, k\, T}{\mu\, m_{\text{H}}}\right)^{1/2}$$

in molecular clouds, with $\Gamma = \frac{3}{5}$ and $\mu = 2.4$,

$$c_s = 0.07 \sqrt{T} \text{ km s}^{-1}$$

DC: 10 – 40 Myr

GMC: 10 – 100 Myr

Blitz 1993 and
Elmegreen 1993 30 – 40 Myr*

Cloud Age	*Method*	*Reference*
>20 Myr	OB: n(stellar generations) > 1	Blaauw 1964, ARAA 2, 213
>10 Myr	34 open clusters/clouds	Leisawitz et al. 1989, ApJS 70, 731

* `star forming lifetime´

Structure of interstellar clouds

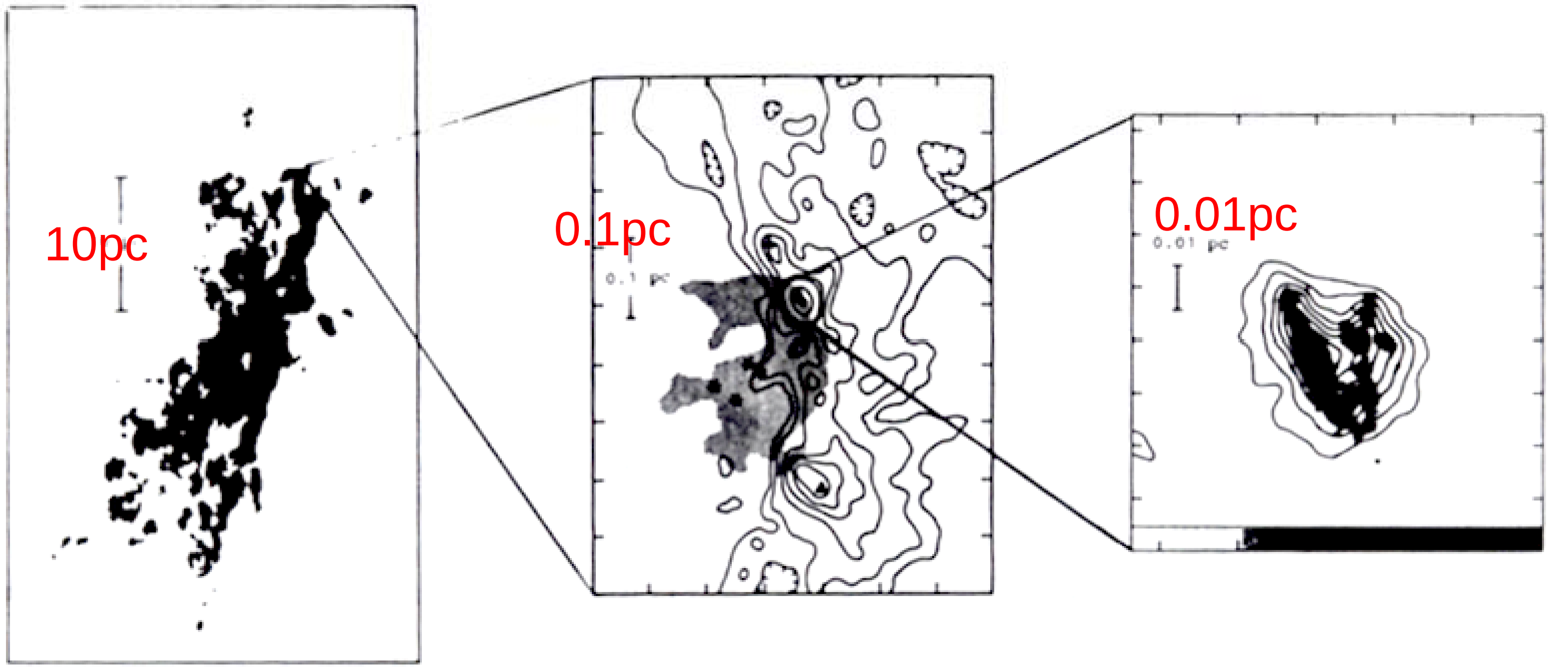
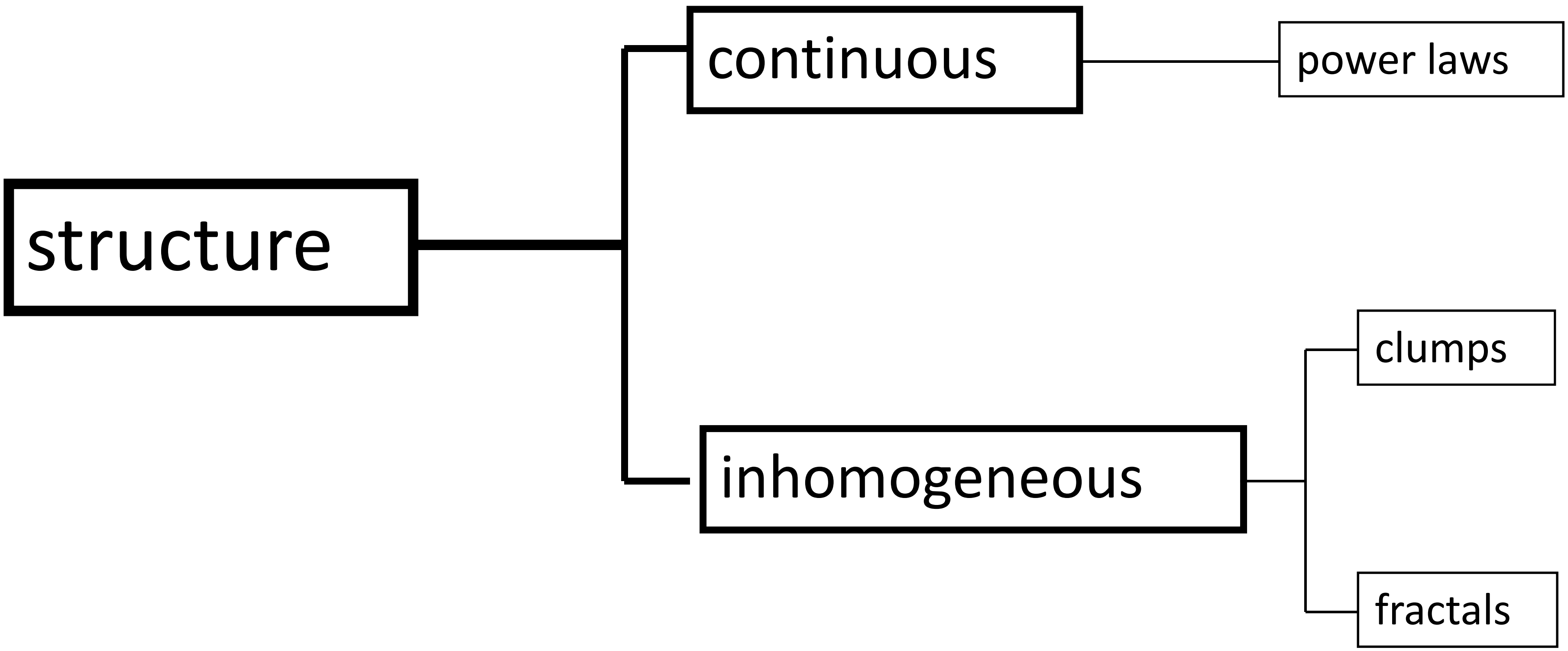
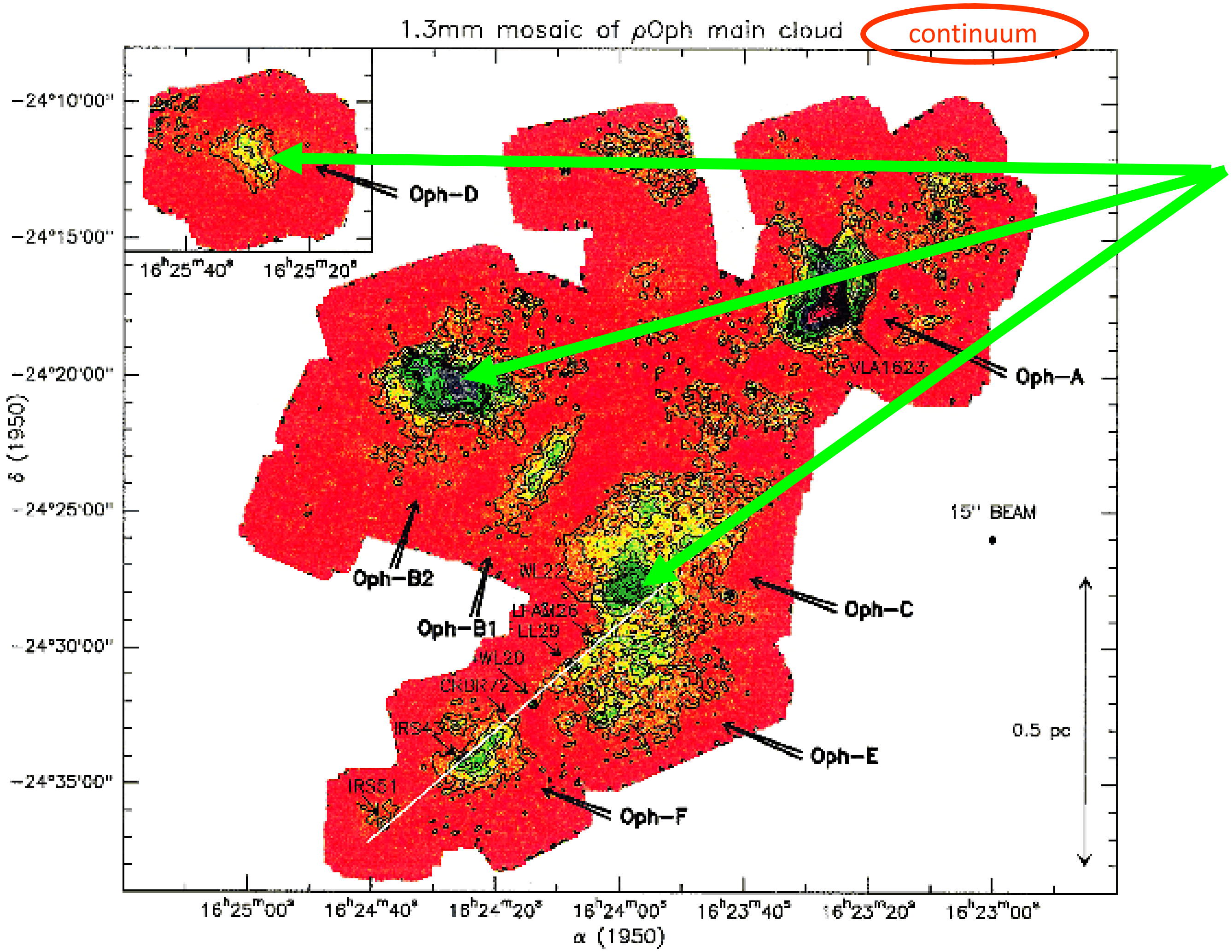


Figure 3. Molecular line maps of Orion A over four orders of magnitude in spatial scale. *Left:* ^{13}CO $1 \rightarrow 0$ map between LSR 6.5 and 7.5 km s^{-1} (Bally et al. 1987, Bell Labs telescope, 90″ beam). *Middle:* CS $2 \rightarrow 1$ map between -0.2 and 18 km s^{-1} LSR (Mundy et al. 1988, OVRO mm interferometer, 7.5″ beam). *Right:* NH_3 (3,2) map (grey shading) between 7.4 and 8.6 km s^{-1} (Migenes et al. 1989, VLA, 1.2″ beam). Contours represent a velocity averaged map, smoothed to 2″.

Structure of interstellar clouds



Structure of interstellar clouds



Motte et al. 1998, AA 336, 150

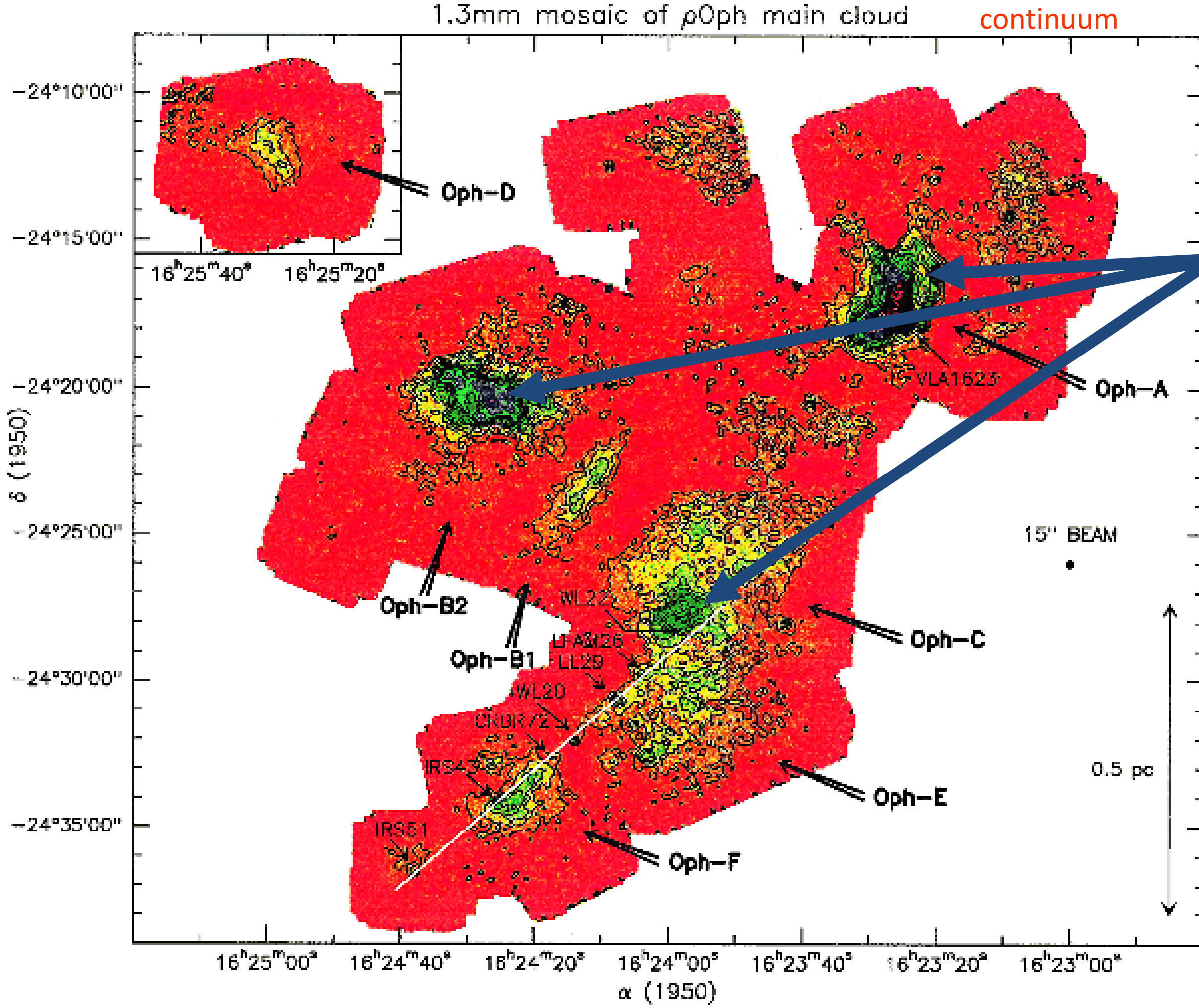
azimuthally averaged isothermal power law fits

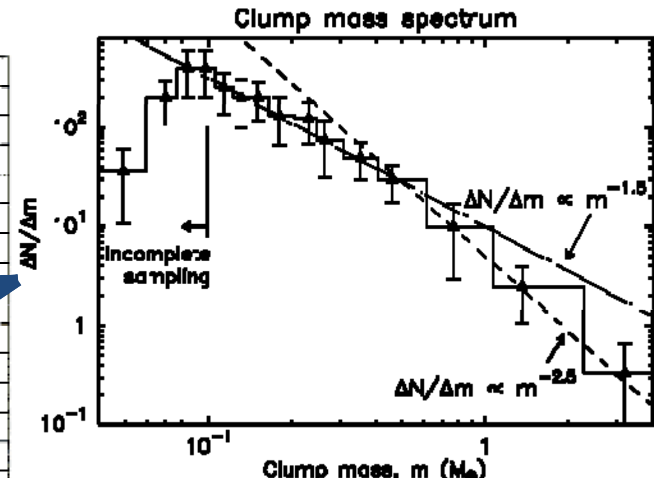
⇒

$\rho(r) \propto r^{\alpha},\ \alpha \approx 0, \quad r \le r_0$

$\rho(r) \propto r^{\alpha},\ \alpha = -2,\ r > r_0$

Inhomogeneous structure of interstellar clouds





clump mass spectrum

$$\frac{dn}{dm} \propto m^{\gamma}$$

with two values of γ

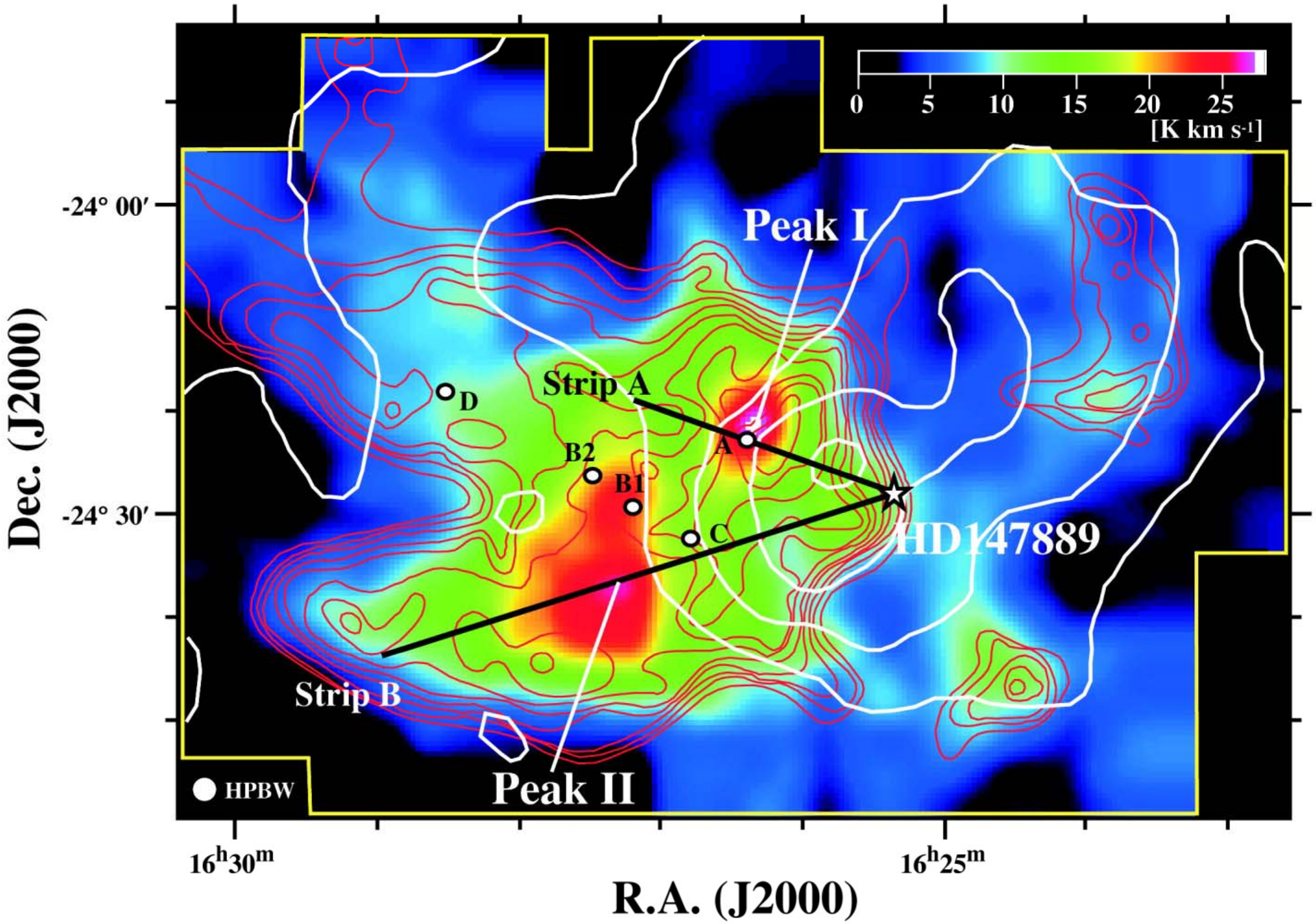
See also 850 μm map by Johnstone et al. 2000, ApJ 545, 327

Motte et al. 1998, AA 336, 150

Inhomogeneous structure of interstellar clouds

Observational evidence from spatial distribution of FIR/submm lines

Neutral Carbon [C I] 609 μm
Ionised Carbon [C II] 157 μm



ρOph (L1688) in [C I] 609 μm, [C II] 157 μm and ^{13}CO 2.7 mm

Kamegai et al. 2003, ApJ 589, 378

Inhomogeneous structure of interstellar clouds

Observational evidence from spatial distribution of FIR/submm lines

Neutral Carbon [C I] 609 μm
Ionised Carbon [C II] 157 μm

→ External UV radiation penetrates to large depths

(e.g., Swiss cheese model)

clump – interclump contrast: > 10^0 to 10^2 in density
< 10^{-1} to 10^{-2} in mass