Observational ISM and Star Formation

This Class (Lecture 4):

Molecular Clouds & Kijeong Yim

Next Class:

Molecular Clouds & Sandor Van Wassenhove

Music: *Earthbound* – Darrin Drda

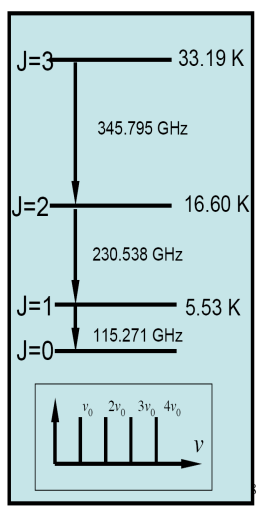
http://www.theendoftheworld.org/astro/toons/cartoon.jpg

Outline

- What are the molecular clouds?
- What is a giant molecular cloud?

Carbon Monoxide

- $J = 1 \rightarrow 0$ ν= 115 GHz λ= 2.6 mm
- $J = 2 \rightarrow 1$ ν= 230 GHz λ= 1.3 mm
- $J = 3 \rightarrow 2$ ν= 345 GHz λ= 0.87 mm
  - Typically λ a few mm for $J = 1 \rightarrow 0$ in heavy diatomics (e.g. CS, SiO, SO)
  - Hydrides (e.g. OH) have much higher rotational frequencies (near λ= 400 μm) because μ is much smaller
- CO J=1-0 at 115 GHz is the molecular analog of the HI 21-cm line

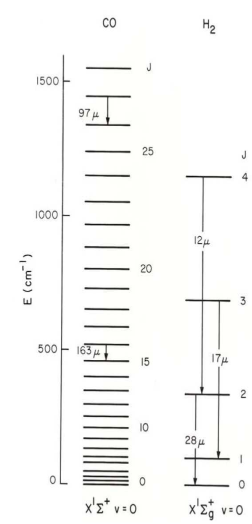


http://zenstoves.net/CO/co.gif

CO vs. H_2

The low abundance of CO ($n_{CO}/n_{H_2} \leq 5 \times 10^{-4}$ if all C is in CO) compared to H_2 or HI is offset by the higher Einstein A values and lower excitation temperatures

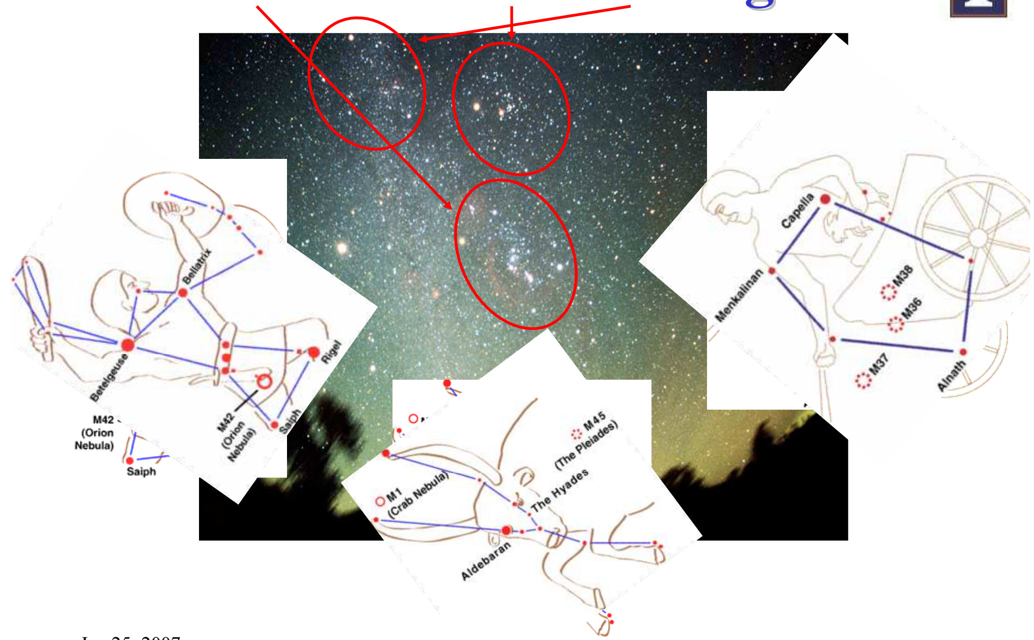
- ^{12}CO lines can be optically thick
- Isotopic lines of CO are important
- The lower abundance means that ^{13}CO or C^{18}O are optically thin when ^{12}CO is optically thick



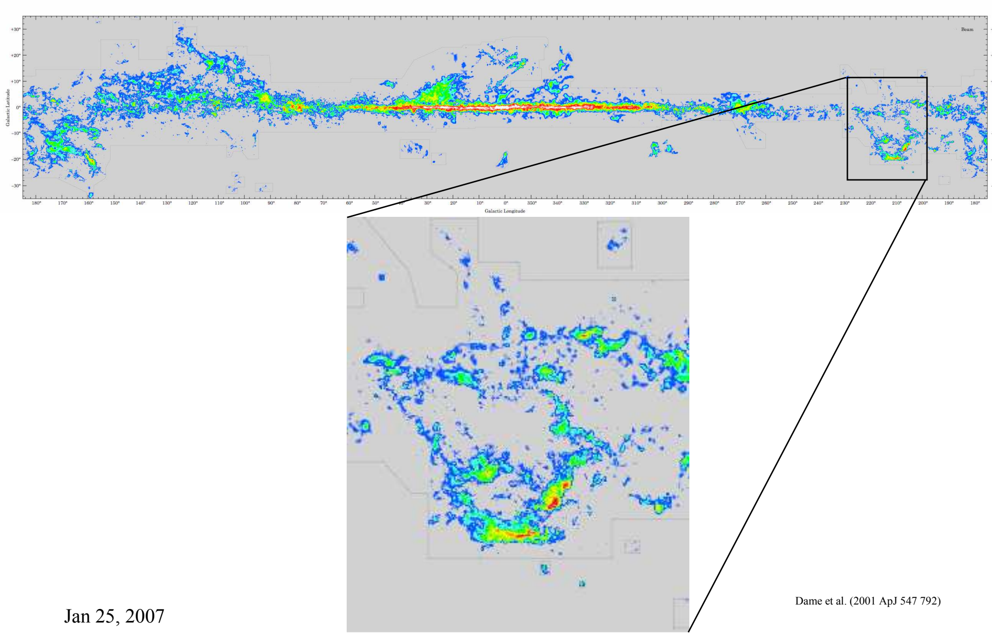
Calculate N_{CO}

- Typically, we use the first refuge of a scoundrel:
  - Assume Local Thermal Equilibrium
    - Single temperature characterizes everything about the level population distribution
  - Least sophisticated, but also requires the least amount of additional observational information
  - Traditionally, the temperature is the physical temperature of the system, but that fails apart in our apps
  - We use a non-kinetic temperature, but no big woop.
  - So the temperature to use is difficult to figure out
- Then to calculate mass of cloud…. Assume geometry, assume X factor…

Orion Taurus Auriga

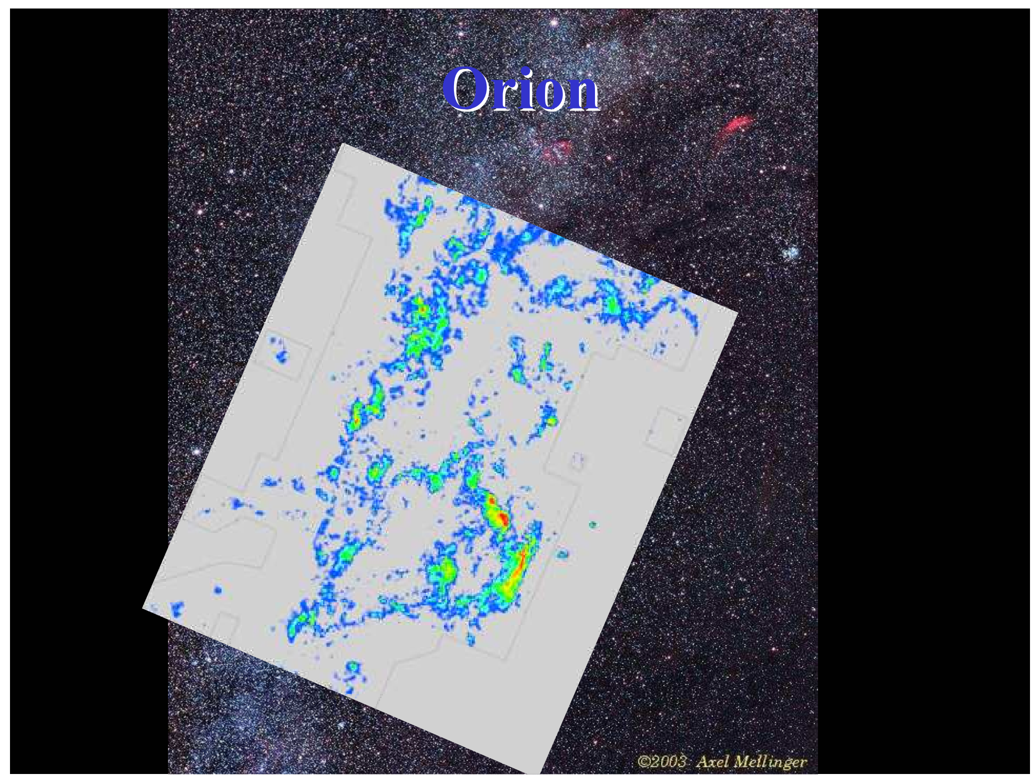


Orion

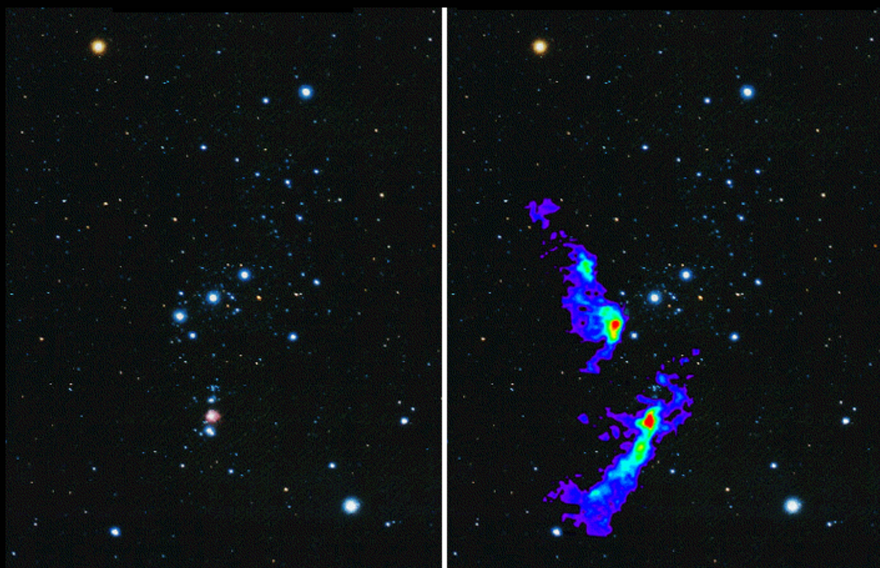


Dame et al. (2001 ApJ 547 792)

Orion

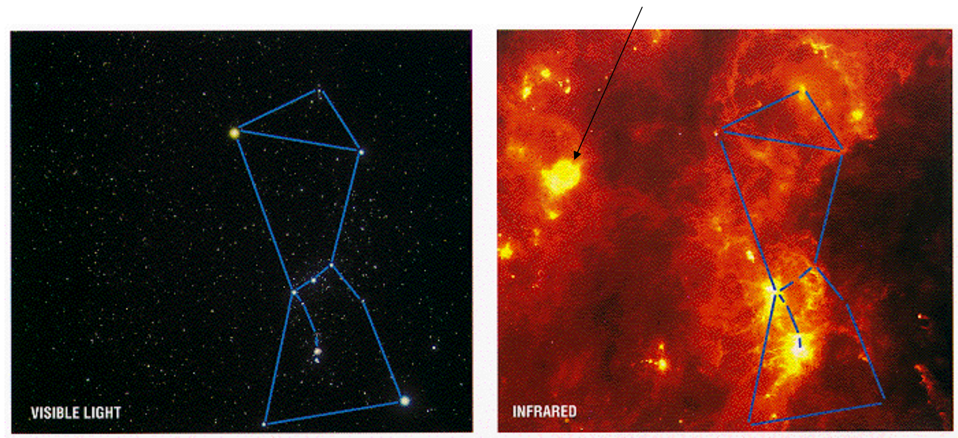


Orion in CO



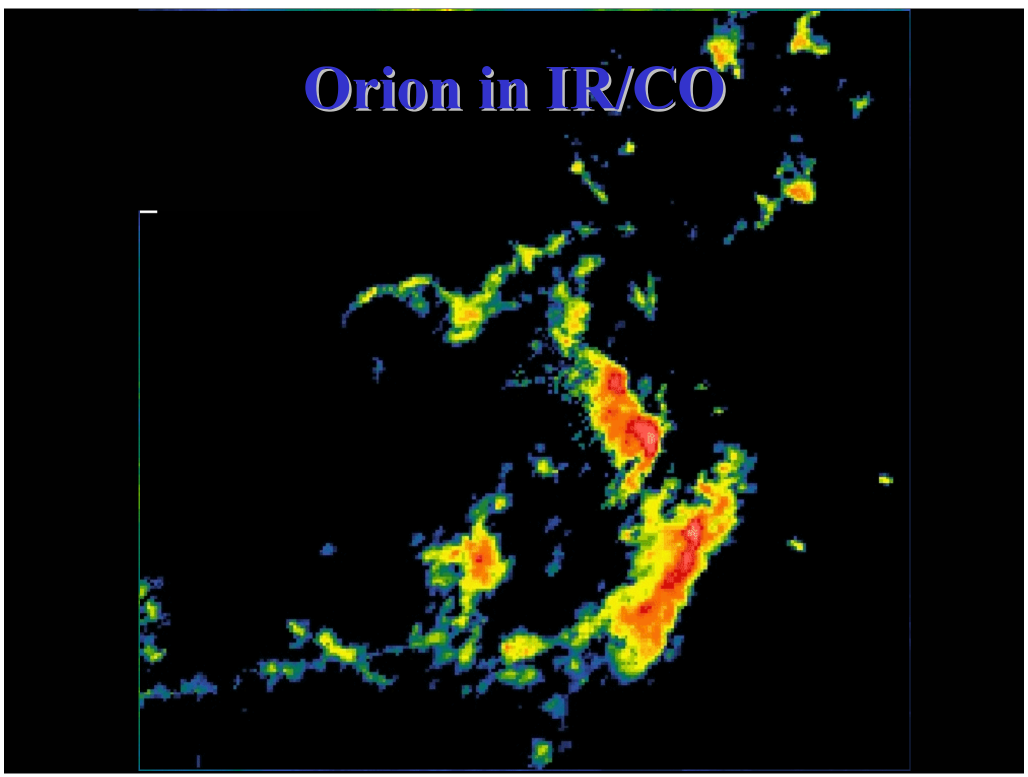
Orion in the IR

Rosette Molecular Cloud



http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_18.pdf

Orion in IR/CO



Orion Finding Chart

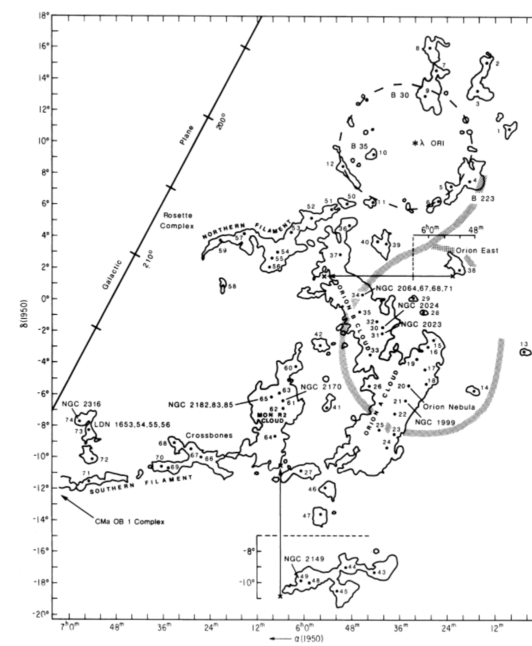
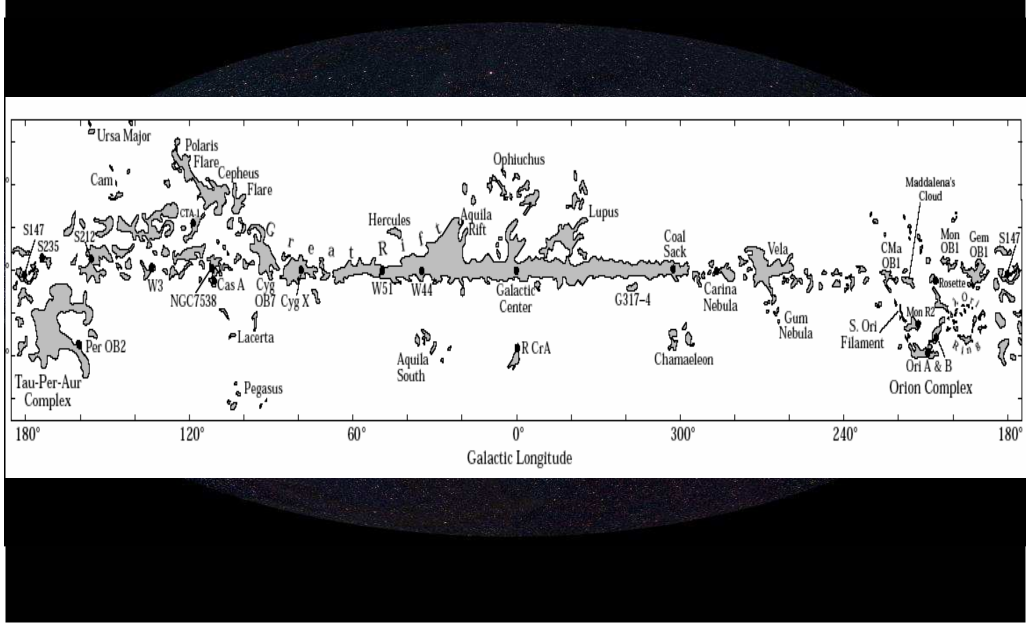


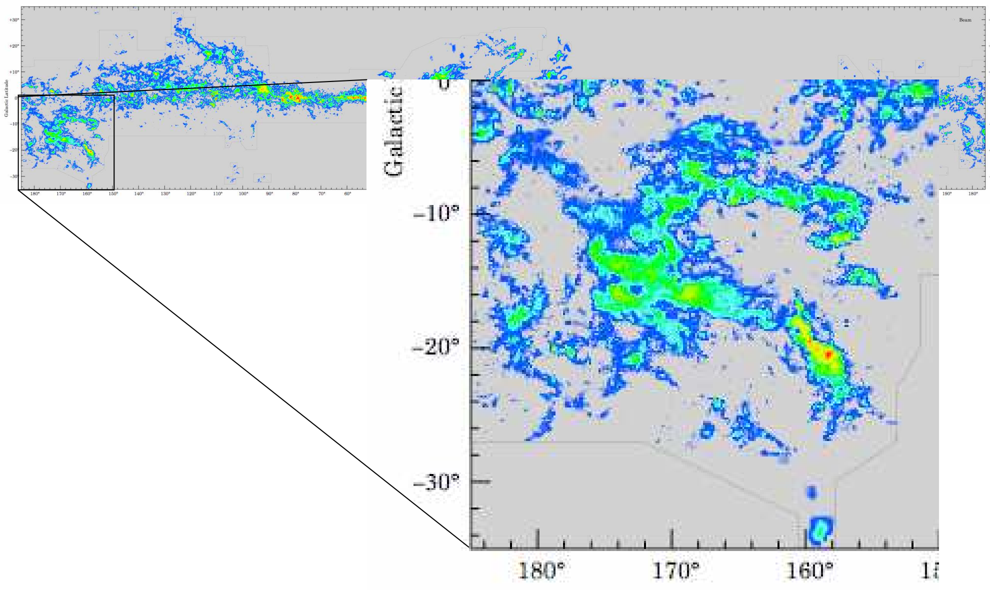
FIG. 3.—Schematic diagram of the molecular clouds: the lowest contour from Fig. 2. Dots with numbers, corresponding to those in Table 1, indicate locations of CO emission peaks. Some NGC numbers indicate the optically prominent objects coincident with CO peaks. The extent of UV emission from Barnard's loop is indicated by the shaded arc (from O'Dell, York, and Henize 1967; Isobe 1973). The dashed line roughly indicates the extent of the λ Ori ring of clouds.

Maddalena et al. 1986 ApJ 303 375

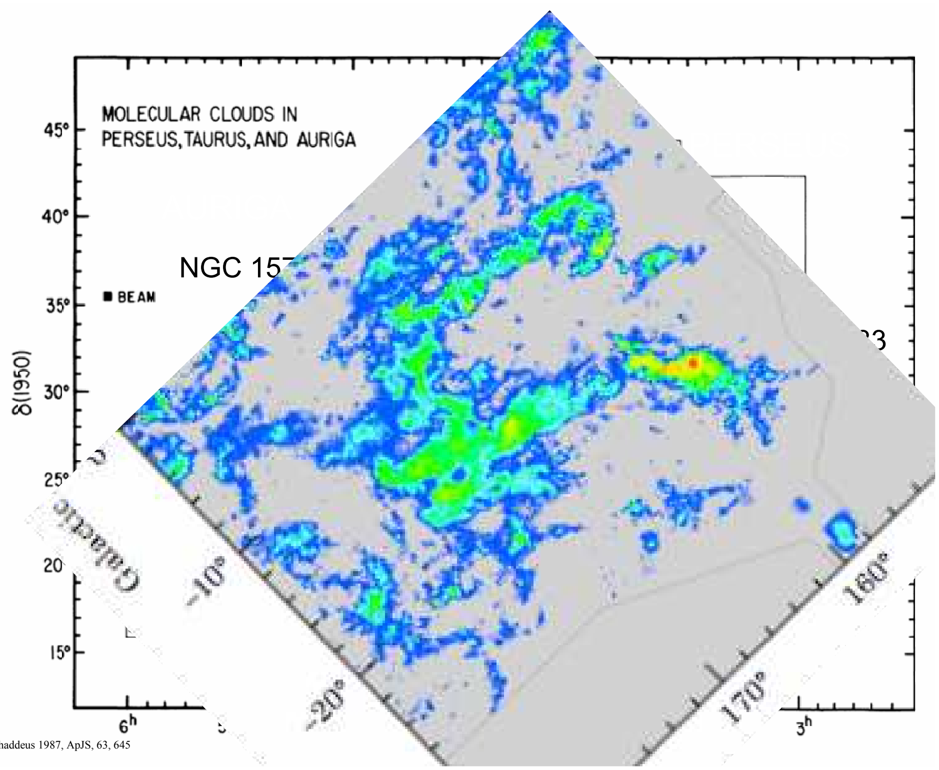
Taurus-Perseus-Auriga



Taurus-Perseus-Auriga Complex



Jan 25, 2007



Ungerechts & Thaddeus 1987, ApJS, 63, 645

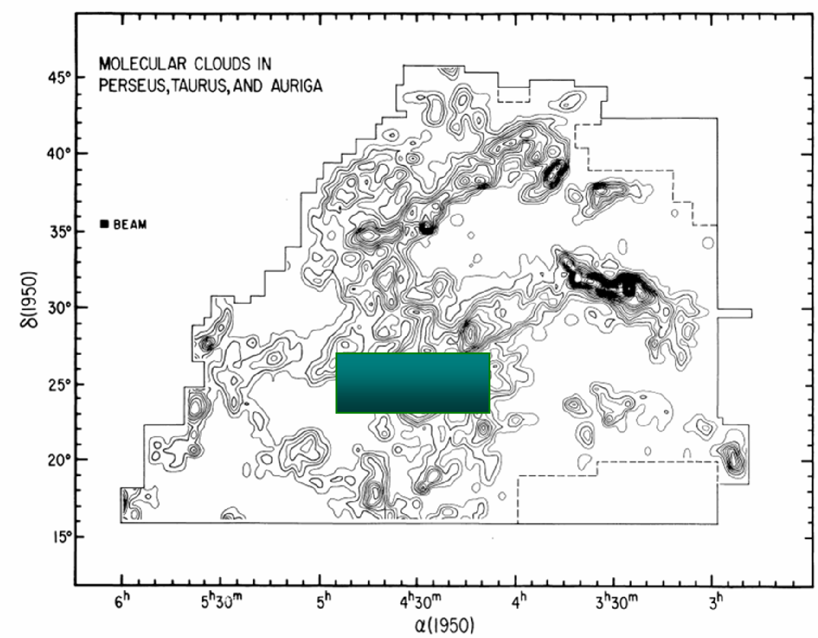
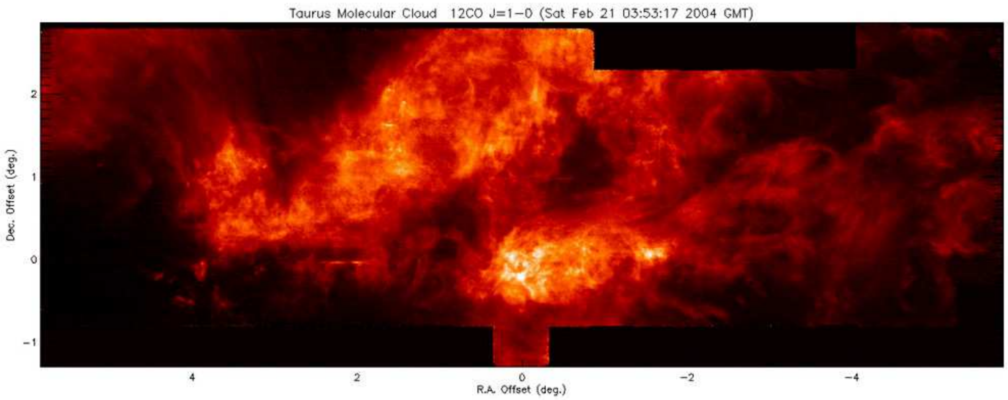


FIG. 1.—Velocity-integrated intensity of CO emission, W_{CO}. The lowest contour is 0.5 K km s^{-1}, and the separation between contours is 1.5 K km s^{-1}. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of $4^m \times 1°$.

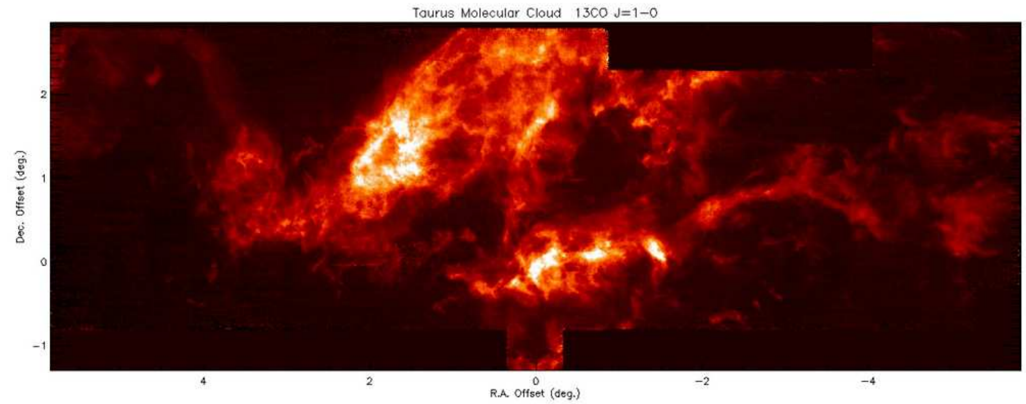
TMC in ^{12}CO



Taurus region in ^{12}CO with the FCRAO 14-m (FWHM = 45″).

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_18.pdf

TMC in ^{13}CO



Taurus region in ^{13}CO with the FCRAO 14-m (FWHM = 45″).

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_18.pdf

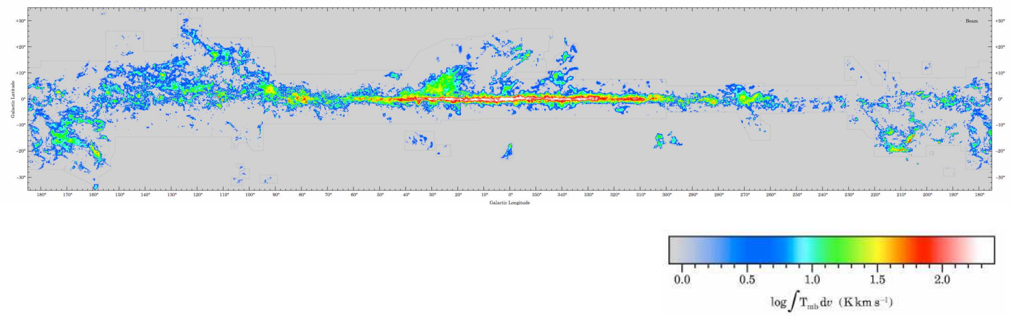
CO and HI

- CO is generally the most easily observed molecular line
  - No molecular cloud free of CO emission
  - GMCs throughout the Milky Way can be detected in CO (1-0) even with a small telescope
- Independent methods show that the velocity-integrated intensity of the J=1-0 line measures $N(H_2)$ to within factor of 2 or better when averaged over **large** region
  - Accepted X factor value ranges from 1.5 to 3 × 10^{20} molecules cm^{-2} (K km s^{-1})$^{-1}$
  - Dame et al. 2001 value was 1.8 × 10^{20}

CO and HI

- CO maps show a much clumpier morphology and different global structure than the broad HI distribution
- Individual molecular clouds and cloud complexes can be identified over much of the Galaxy
  - Although CO lines are often optically thick there are different velocities for different Galactic radii and so we can find clouds over a large section of the Galactic disk
  - In some regions the clouds complexes are confused, and there is no definitive picture of the structure along these lines of sight

Distribution of Molecular Clouds

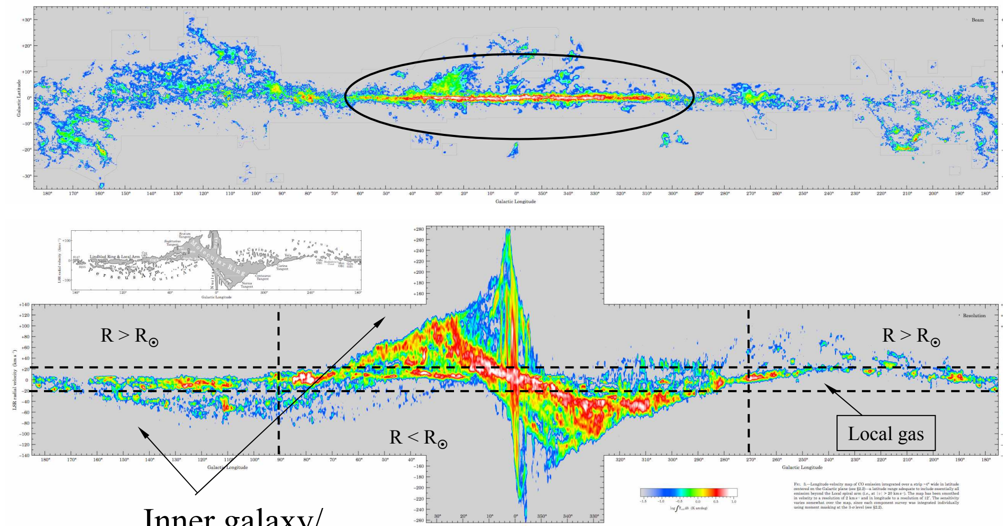


Dame et al. 2001: The CO distribution is plane of Galaxy is thin

- Vertical extent ±45-75 pc over much of the disk
- Similar to that of OB associations
- Flares out to ±100-200 pc

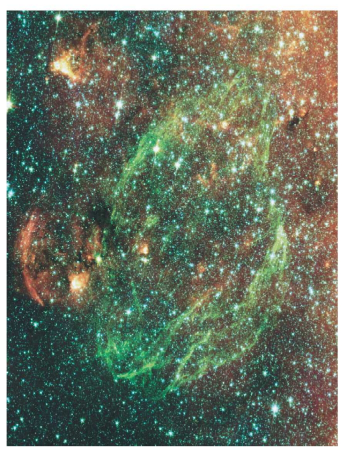
http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_18.pdf

The Molecular Ring



Giant Molecular Complexes

- The strong (red-white) peaks in the (l, v) maps are ***giant molecular complexes***
  - $M \approx 10^5 - 10^6\ M_\odot$
  - $\sigma \approx 15$ km/s or larger
- Appear to be well defined, coherent structures
  - ~80% of the total molecular gas is contained within such structures
- Nearby examples include W44 (3 kpc) and the cloud associated with the Cas A SNR

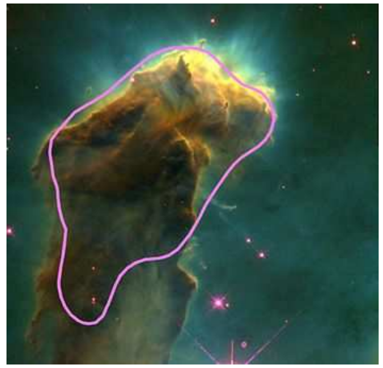

M44: Reach et al. 2006, ApJ, 131, 1479

What is a Molecular Cloud?

- Molecular clouds (by definition) are regions where the mass is primarily molecular
  - Much of the volume is not necessarily molecular
  - Highly structured with large range of density
  - Filling factor is low
    - Perhaps less than ~ 0.2
- Most of the molecular ISM is in the form of giant molecular clouds
  - $M \sim 10^{5\text{-}6}\ M_\odot$ with a sharp cut off at $6 \times 10^6\ M_\odot$
  - $D \sim 50$ pc
  - $< n_{H2} > \sim 100$ cm^{-3}
- What sets the upper mass range?
  - Galactic tidal field?
  - Feedback from massive stars?

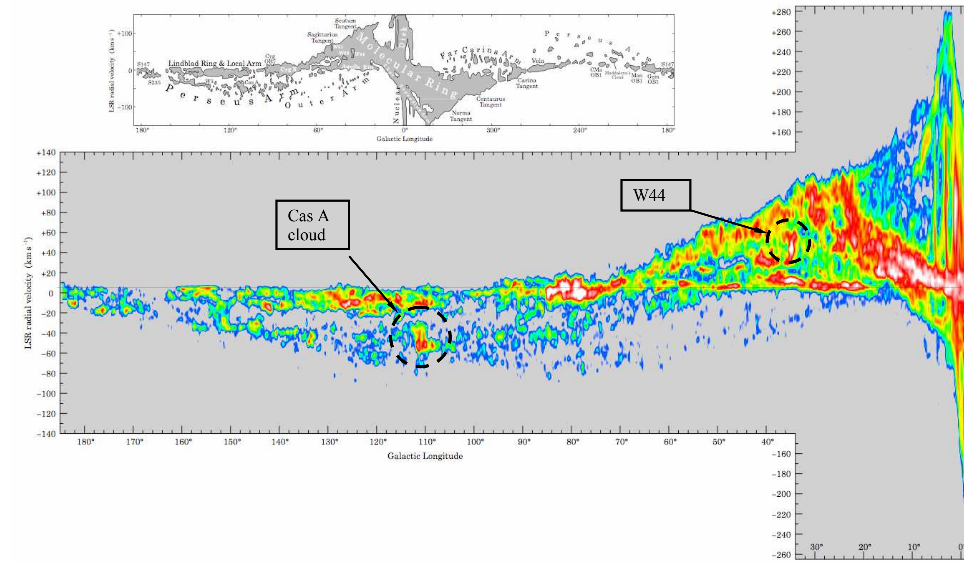
What is a Molecular Cloud?

- Molecular clouds:
  - Contain molecules (but don't forget HI)
  - Self-gravitating
  - Magnetized
  - Turbulent
    - The central role of gravity, not their molecular composition, that distinguishes them from any other phase of the ISM
- Stars form only in molecular clouds
  - Understanding star formation starts with understanding molecular clouds

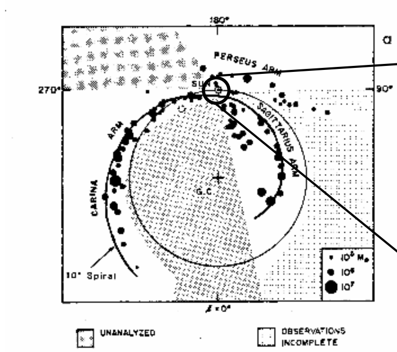


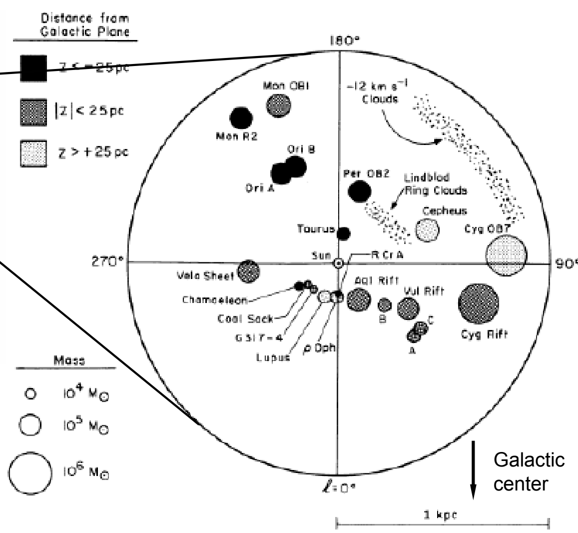
http://hubblesite.org/newscenter/archive/releases/1997/34/image/m/format/web

Nearby GMCs



Nearby Molecular Clouds





- Taurus is the nearest molecular cloud
  - Site of low-mass star formation
- Nearest site of OB star formation is Orion
- Nearest cloud complex is the Cygnus rift/Cygnus OB7

http://astro.berkeley.edu/~ay216/06/NOTES/ay216_2006_18.pdf

Molecular Clouds

- HI or diffuse molecular clouds are kept from dispersing from pressure balance of internal motion to the rarefied warm medium
- Larger molecular clouds are dominated by self-gravity

Table 3.1 Physical Properties of Molecular Clouds

Cloud Type	A_V (mag)	n_{tot} (cm^{-3})	L (pc)	T (K)	M ($M_\odot$)	Examples
Diffuse	1	500	3	50	50	ζ Ophiuchi
Giant Molecular Clouds	2	100	50	15	10^5	Orion
Dark Clouds						
Complexes	5	500	10	10	10^4	Taurus-Auriga
Individual	10	10^3	2	10	30	B1
Dense Cores/Bok Globules	10	10^4	0.1	10	10	TMC–1/B335

The Formation of Stars. Steven W. Stahler and Francesco Palla

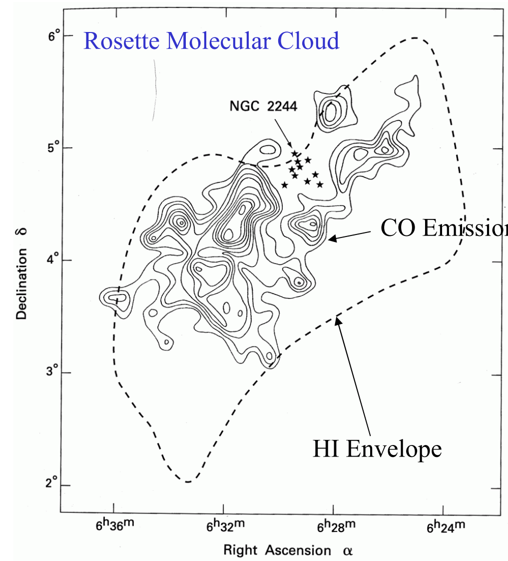
ISBN: 3-527-40559-3

Properties of Local GMCs

Mass	1-2 x 10^5 $M_\odot$
Mean diameter	45 pc
Projected surface area	2100 pc^2
Volume	9.6 x 10^4 pc^2
Volume density (H_2)	~ 50 cm^{-3}
Mean column (H_2)	3-6 x 10^{21} cm^{-2}
Surface density	~ 4 kpc^{-2}
Mean separation	~ 500 pc

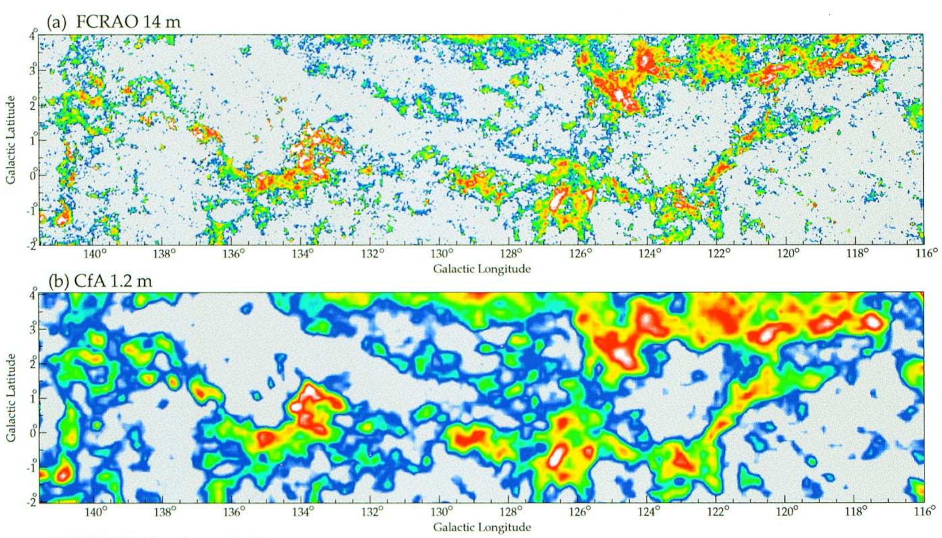
Molecular Clouds

- Typical giant cloud survives ~ 3 × 10^7 years before destroyed by embedded OB stars
- On average, converts 3% of mass to stars
- Every OB association closely associated with GMCs.



Stahler: Formation of Stars

Spatial Structure



Dense Gas Tracers

Molecule	Transitions	Frequency (GHz)	E/k (K)	n_{crit} (cm^{-3}) @ 10 K
$^{12}C^{16}O$	1-0	115.2	5.5	1100
	2-1	230.5	16.6	6700
	3-2	345.7	33.2	2 x 10^4
CS	1-0	49.0	2.4	4.6 x 10^4
	2-1	98.0	7.1	3.0 x 10^5
NH_3	(1,1)	23.7	1.1	1.8 x 10^3
	(2,2)	23.7	42	2.1 x 10^3

Density Structure in Molecular Cloud Cores

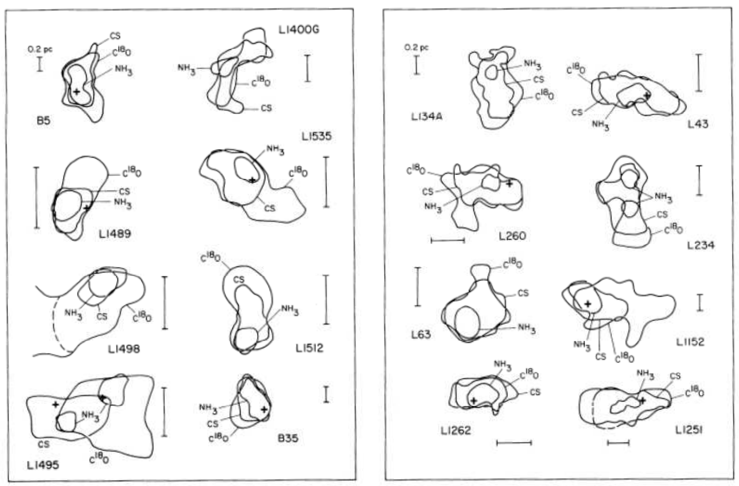


Fig. 1*a* Fig. 1*b*

Fig. 1.—Half-maximum intensity contours of 16 dense cores in dark clouds, in the 1.3 cm $(J, K) = (1,1)$ lines of NH_3, from Benson & Myers (1989), and in the 3.0 mm $J = 2 \rightarrow 1$ line of CS, and the 2.7 mm $J = 1 \rightarrow 0$ line of $C^{18}O$, from Fuller (1989). For each map, North is up, East is left, and the linear scale 0.2 pc is indicated. A cross indicates an associated star.

Myers et al. 1991 ApJ 376 561

Orion A as a Typical Cloud

- Cloud A (L1641) exhibits some typical features of GMCs
  - Elongated
    - Parallel to the plane of the Galaxy
  - Strong velocity gradient (rotation)
  - GMCs have well defined boundaries
    - GMCs are discrete objects
  - Lumpy
    - Near unity surface filling factors (traced by optically thick ^{12}CO 1-0)
  - OB associations form in GMCs