Astronomy 496/596:

Observational ISM and Star Formation

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http://eeyore.astro.uiuc.edu/~lwl/classes/astro596/spring07

This Class (Lecture 3):

Molecular Clouds

Next Class:

Molecular Clouds

Music: *Million Miles Away from Home* – Dune

Outline

- HI and CO
- What are the molecular clouds?
- What is a giant molecular cloud?

H I

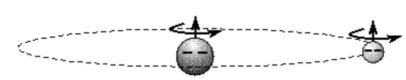
1 Hydrogen 1
H
1.008

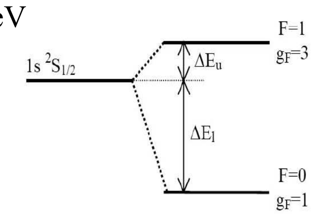
- Total mass of atomic H exceeds H_2 in the Galaxy.
- Atomic H is the reservoir that ultimately produces molecular clouds.
- A new dimension entered radio astronomy with the detection of the λ = *21 cm line of atomic hydrogen*
  - Long wavelength is less affected by extinction.
  - Generally in emission but also in absorption against a background continuum radio source, e.g., an HII region
  - 21 cm line measures the quantity of interstellar HI
  - Doppler shift gives radial velocities
- **What causes this emission?**

Spin Flip

- Consequence of the proton and electron spins
- H atom consists of 1 proton + 1 electron
  - Electron: spin S=1/2
  - Proton: nuclear spin I=1/2
  - Total spin: $F = S + I = 0$ or 1
- Hyperfine interaction leads to splitting of ground level:
  - $F = 1$ $g_u = 2F+1 = 3$ $E_u = 5.87\times10^{-6}$ eV
  - $F = 0$ $g_l = 2F+1 = 1$ $E_l = 0$ eV

Neutral atomic Hydrogen creates 21 cm radiation



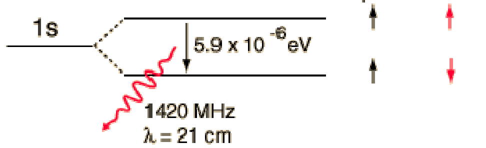


http://www.astronomynotes.com/ismnotes/s3.htm

Hyperfine

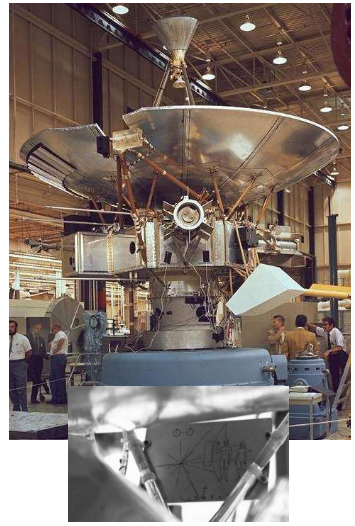
In $^{1}H\ ^{2}S_{1/2}$ the $F = 0$ and $F = 1$ have zero electric dipole

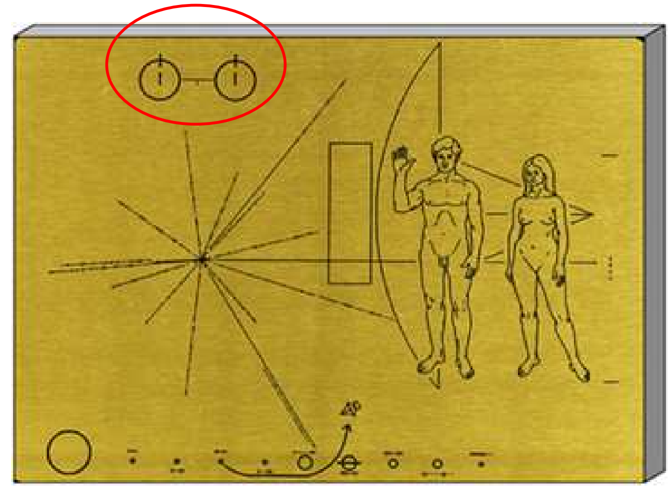
- F=0 → 1 is a magnetic dipole transition
  - $A_{10} = 2.85 \times 10^{-15}\ s^{-1}$
- Or a mean lifetime of ≈ 11 Myr
- Collisionally excited
- Usually collisionally de-excited, but some emit
- With enough atoms, can gather an appreciable radio signal
- The signal is directly proportional to the to column density (i.e. # of atoms/cm^{-2}) for N(HI) << 5.5×10^{20} cm^{-2}



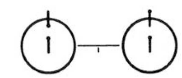
http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html
http://www.leapsecond.com/pages/unix/

Pioneer 10





Hyperfine unit used on Pioneer 10 plaque



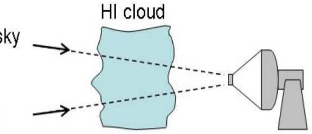
Radiative Transfer: LTE

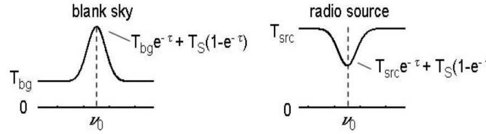
$$T_B = T_{BG} e^{-\tau} + T_s (1 - e^{-\tau})$$

- Can rewrite the standard radiative transfer equation with a brightness temperature (think radio astronomer perversion)
- In LTE the slab of material is at a single temperature that characterizes everything about the level population distribution
  - T_B is the observed brightness temperature
  - T_{BG} is any power from “behind” the slab
  - T_s is the power from the slab (T_{spin} in this case)
  - τ is the optical depth of the slab

Probing the ISM

- The excitation temperature generally is $T_{spin} = T_{kinetic}$ (i.e. dominated by collisions).
- Can observe an extended source and an extragalactic bright source.
- Have to assume the cloud properties don't change between ON/OFF positions.
- 2 equations and 2 unknowns (τ and T_s), can derive both column density and temperature!

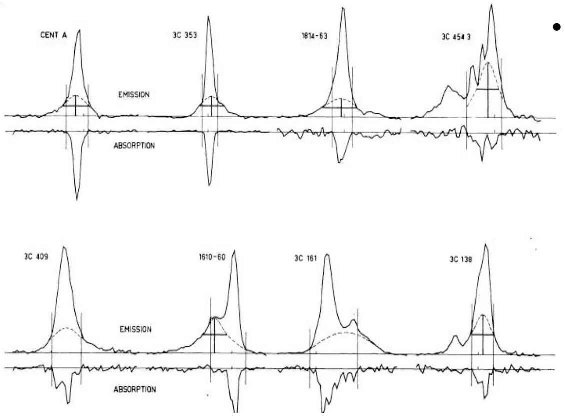




Assumption
$T_s < T_{src}$

http://www.strw.leidenuniv.nl/~dave/ISM/lecture7.pdf

Observational Evidence for 2 Phases: CNM/WNM



Radhakrishnan 1972 ApJS 24 15

- Evidence for the CNM/WNM
  - Clark 1965 ApJ 142 1298
  - Radhakrishnan 1972 ApJS 24 15
  - Dickey 1979 ApJ 228 465
  - Payne 1983 ApJ 272 540

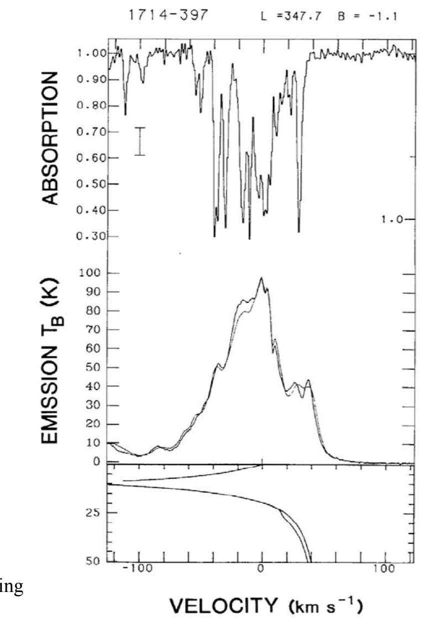
- Good agreement between narrow absorption lines and narrow peak emission lines: $\Delta V \approx 3$ km/s
- There is excess emission outside the region over which absorption occurs (dashed lines): $\Delta V \approx 9$ km/s

Emission and Absorption

Note that the absorption features are sharper than the corresponding emission spectrum

Absorption: various clumps of cold clouds with different velocities (Cold Neutral Medium). Not all EG source show absorptions– small filling factor.

Emission: warm gas (Warm Neutral Medium). Ubiquitous emission– large filling factor.



http://www.strw.leidenuniv.nl/~dave/ISM/lecture7.pdf

CNM

- 40% of atomic neutral gas
- Cold diffuse clouds with $T \approx 70$ K
  => narrow absorption + emission components
- CNM occurs in clumps throughout the disk of the Milky Way with $z \approx 100$ pc
  - Typically in disk: $N(\mathrm{HI})_{full\ thickness} \approx 6\times10^{20}$ cm^{-2}
  - Locally: $N(\mathrm{HI}) \approx 4 \times 10^{20}$ cm^{-2}
    - We live in a "H I hole"

http://www.cnm.com.br/

WNM

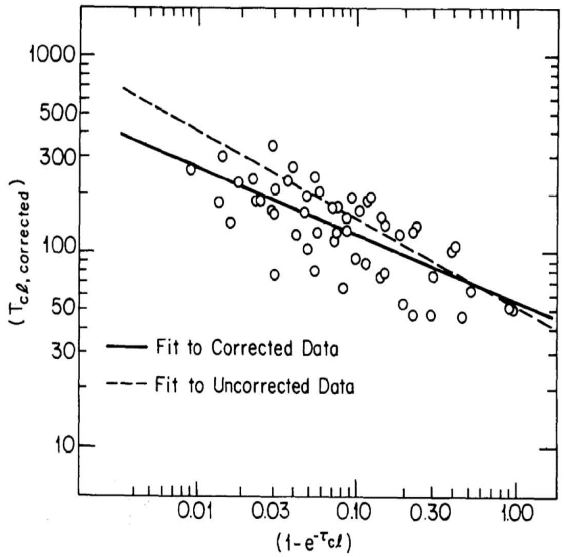
- 60% of atomic neutral gas
- Broad emission component, but temperature difficult to estimate
  - $\Delta V \approx 9$ km s^{-1}=> $T < 10000$ K
  - Limits on τ => $T > 3000$ K

  → T ≈ 8000 K
- WNM is distributed throughout Milky Way with substantial filling factor
  ⇒"raisin-pudding"model of ISM
- Large scale height (Gaussian $z \approx 250$ pc and exponential $z \approx 500$ pc), which means >> than CNM)
  => warm H I halo?

http://216.54.196.65/wwvp/westminster_neighborhood_ministries/images/wnm%20movie.jpg

Anticorrelation

The higher the optical depth (τ), the lower the temperature.



http://www.strw.leidenuniv.nl/~dave/ISM/lecture7.pdf

Making Molecular Clouds

- Now we have stuff in between stars (ISM)
- But we want to make stars.
- Stars form in GMCs, so how do we make those?
  - CNM and WNM are in pressure equilibrium (2 phases)
  - Can not consider molecular gas as an ISM phase → gravity dominated

The Problem

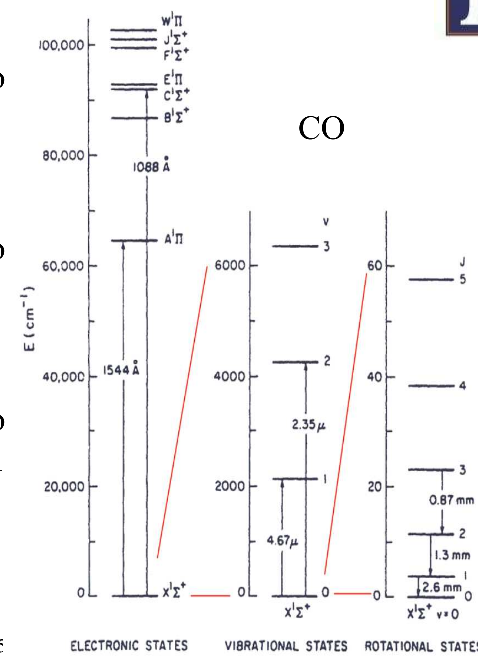
- How to trace molecular material?
- Molecular clouds are mostly made from H_2
- And H_2 does not play well, emission-wise
- One of the most difficult to detect molecules under typical molecular cloud conditions
  - No permanent dipole moment, must radiate through a relatively slow and weak quadrupole transition ($\Delta J=2$)
- Lucky for us, the next abundant molecule, CO, comes to the rescue!

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

Molecular Emission

- Energy difference between two electronic states: typically a few eV (10,000 cm^{-1})
  → ***VIS and UV***
- Energy difference between two vibrational states typically 0.1-0.3 eV (~500-3000 cm^{-1})
  → ***IR***
- Energy difference between two rotational states typically 0.001 eV (~10 cm^{-1})
  → ***(sub)millimeter***

CO



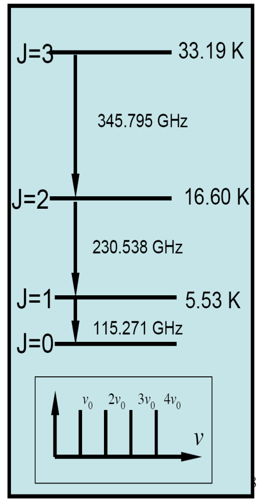
http://www.strw.leidenuniv.nl/~dave/ISM/lecture12.pdf

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

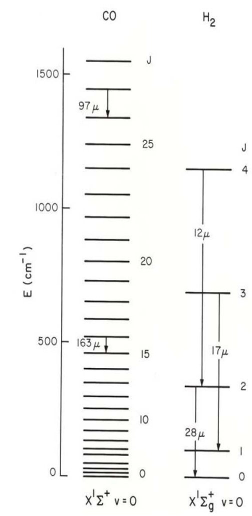


http://zenstoves.net/CO/co.gif

CO vs. H_2

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

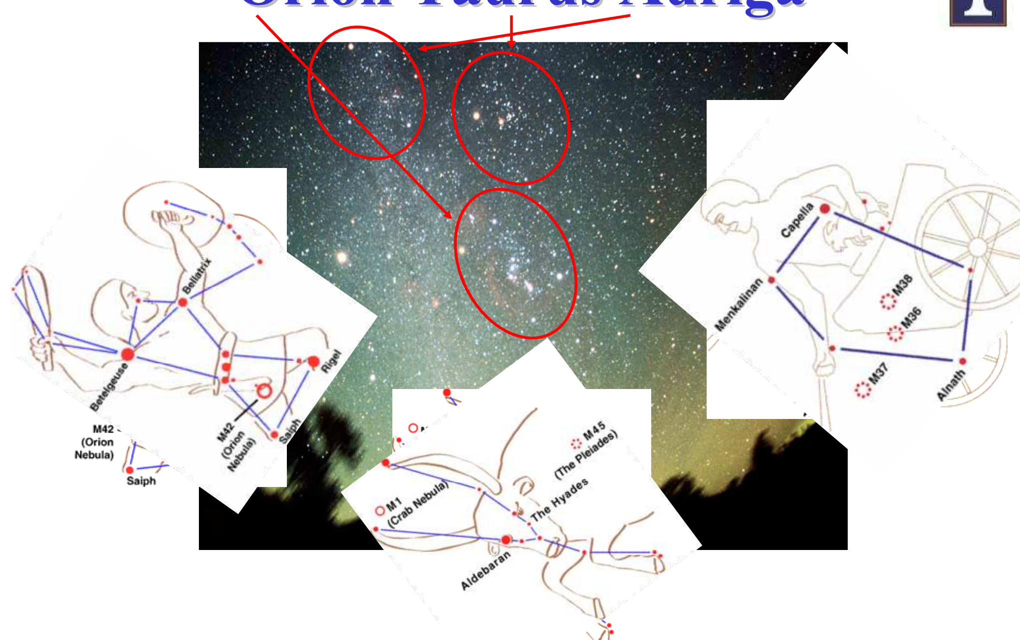
  – ^{12}CO lines can be optically thick
  – Isotopic lines of CO are important
  – The lower abundance means that ^{13}CO or $C^{18}O$ are optically thin when ^{12}CO is optically thick



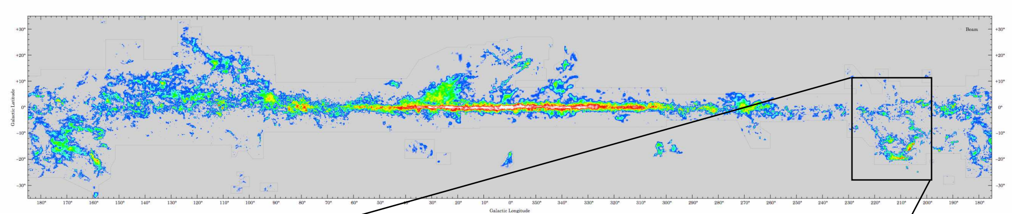
Calculate N_{CO}

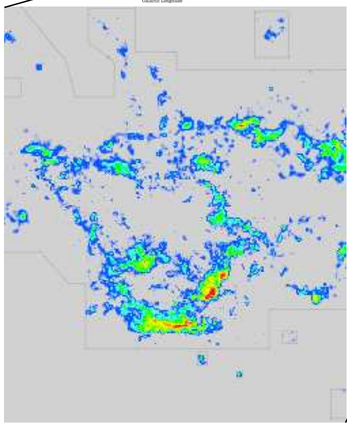
- Typically, we use the first refuge of a scoundrel:
  – Assume Local Thermal Equilibrium
    - Single temperature characterizes everything about the level population distribution
  – Least sophisticated, but also requires the least amount of additional observational information
  – Traditionally, the 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

Orion Taurus Auriga



Orion

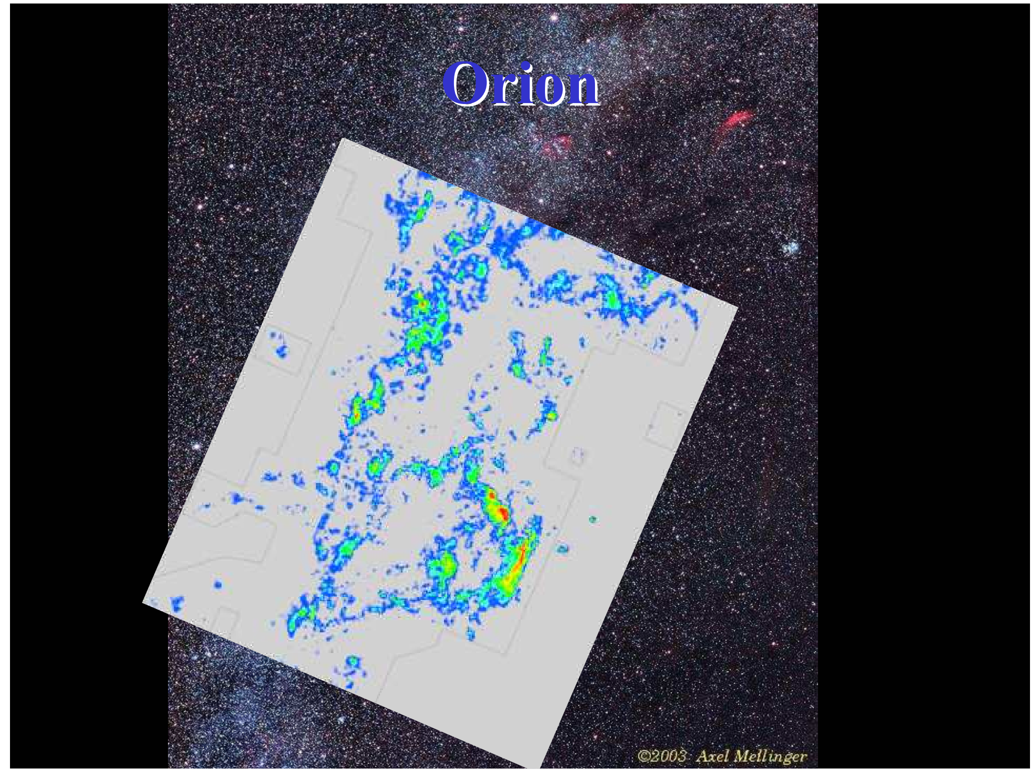




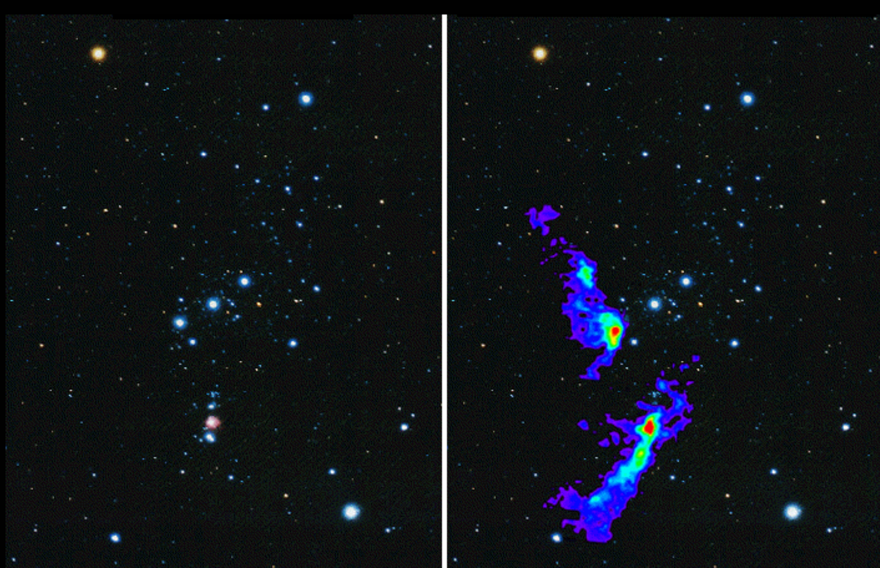
Dame et al. (2001 ApJ 547 792)

Jan 23, 2007

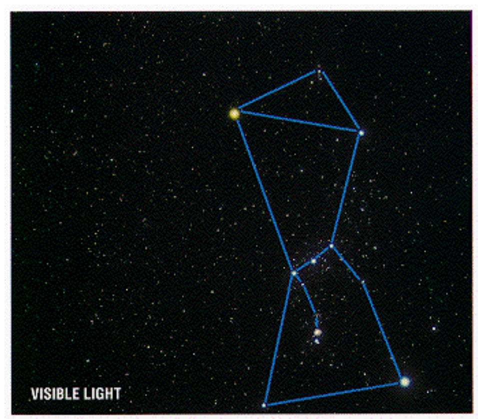
Orion

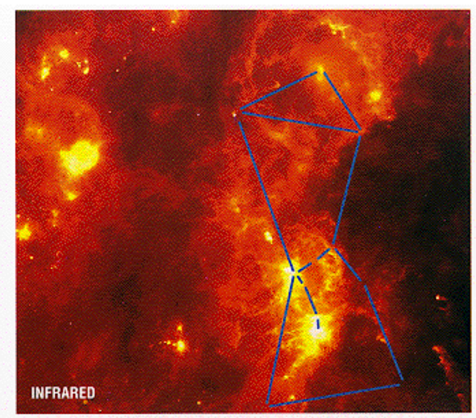


Orion in CO



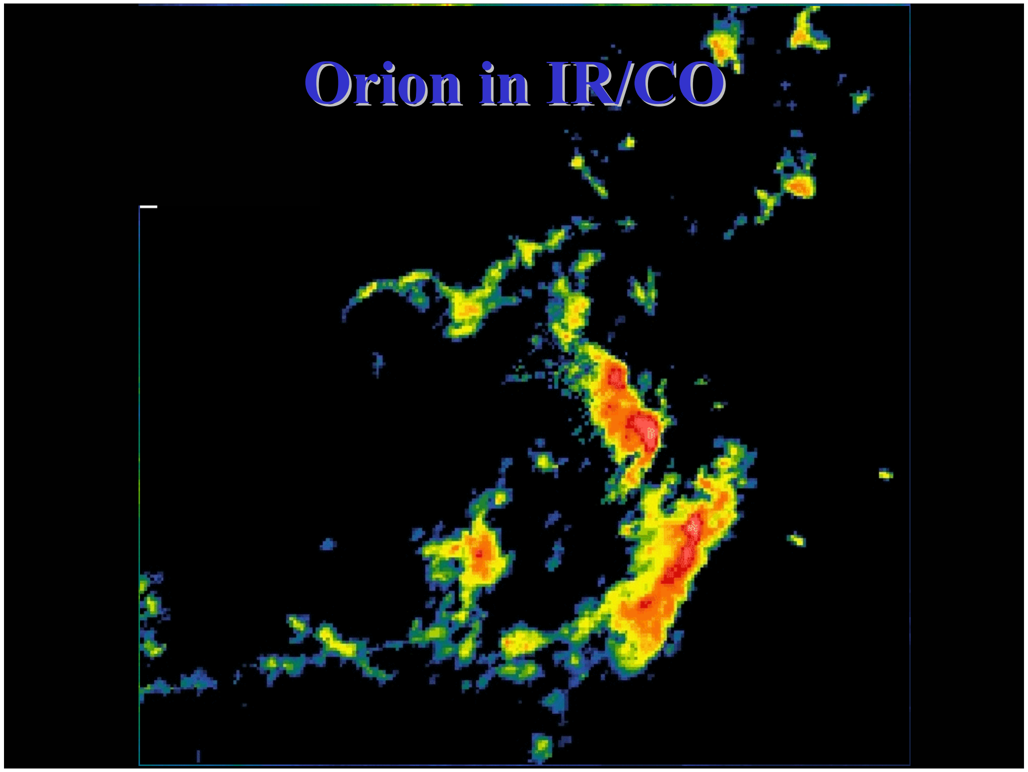
Orion in the IR





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

Orion in IR/CO



Orion Finding Chart

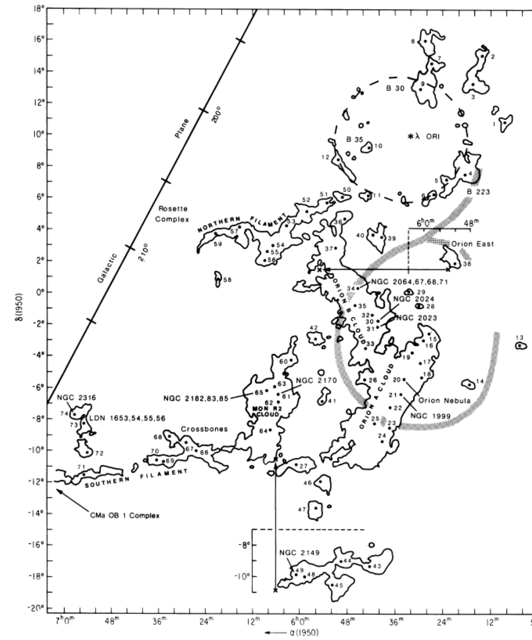
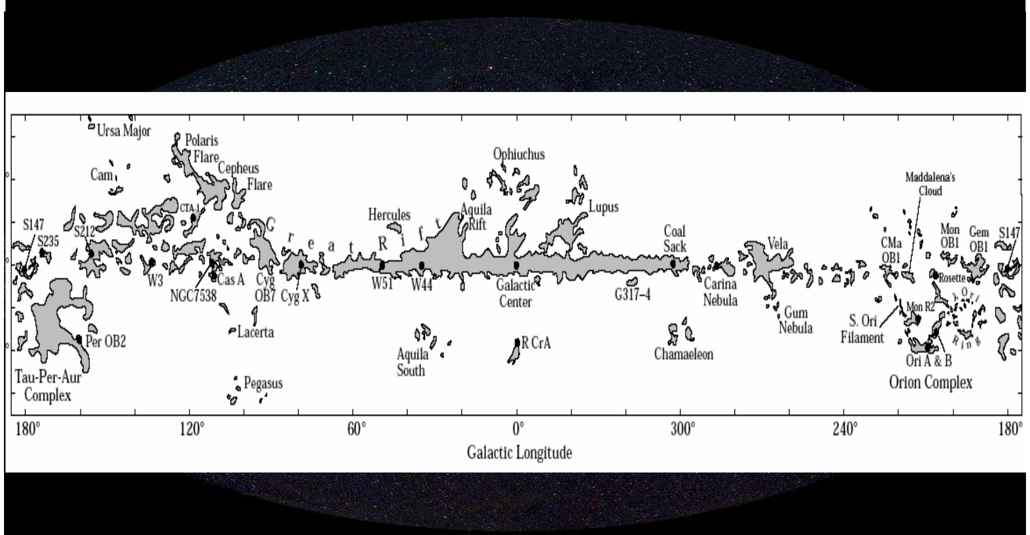


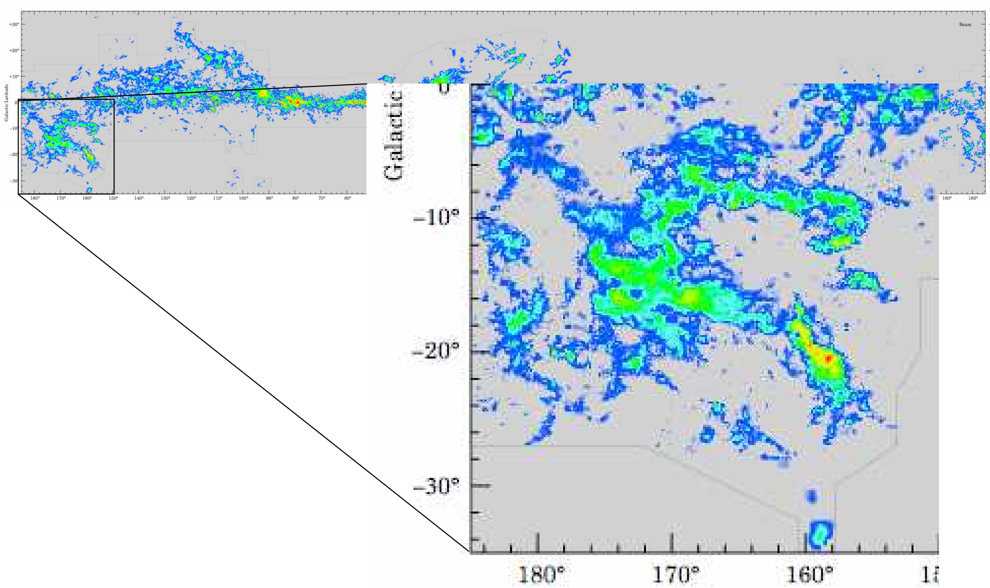
FIG. 3.—Schematic diagram of the molecular clouds: the lowest contour from Fig. 2. Dots with numbers, corresponding to those in Table 1, indicate locations of CO emission peaks. Some NGC numbers indicate the optically prominent objects coincident with CO peaks. The extent of UV emission from Barnard's 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.

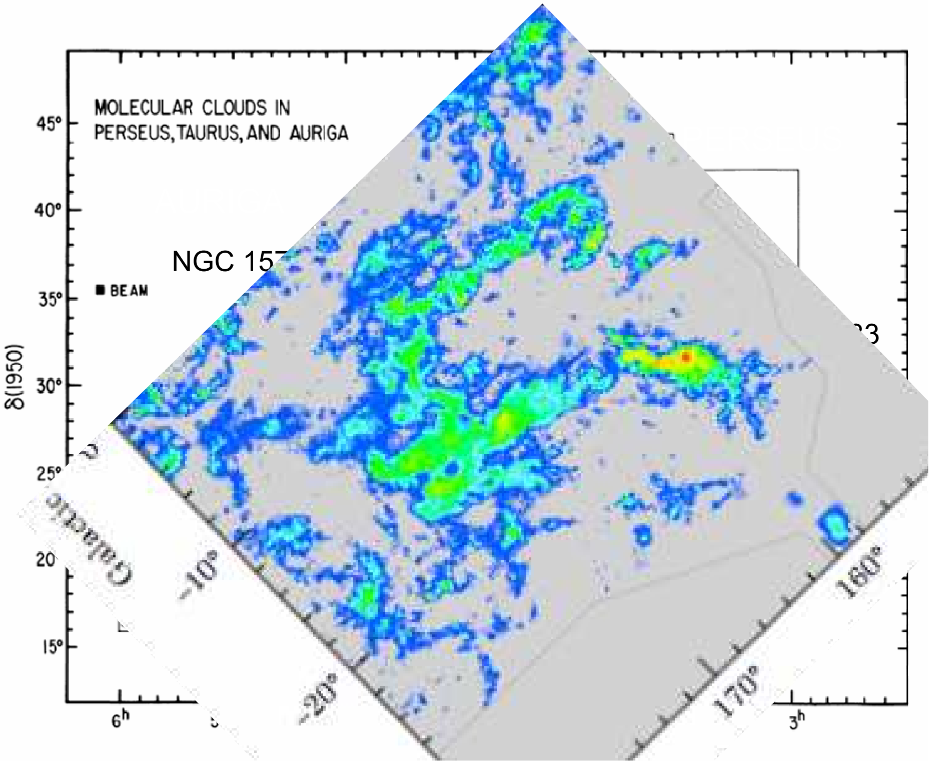
Maddalena et al. 1986 ApJ 303 375

Taurus-Perseus-Auriga



Taurus-Perseus-Auriga Complex





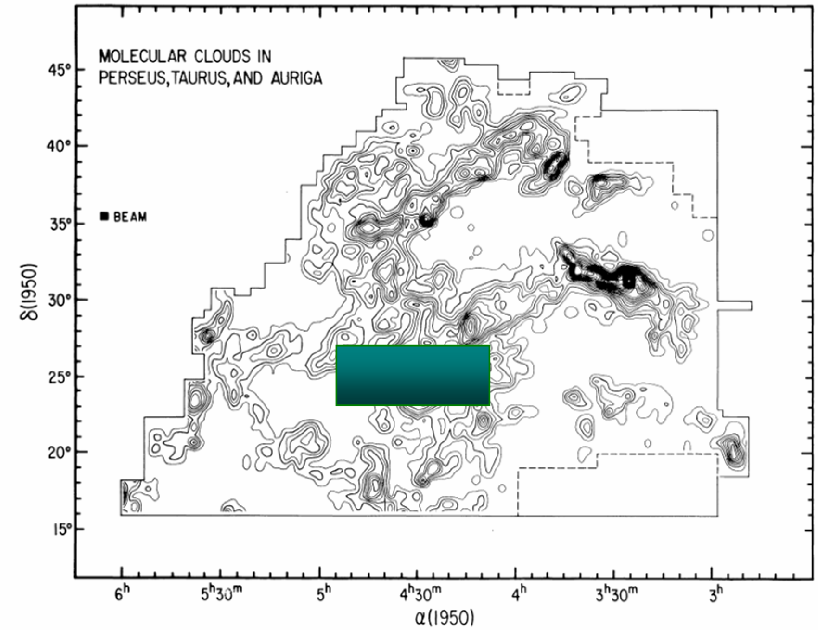
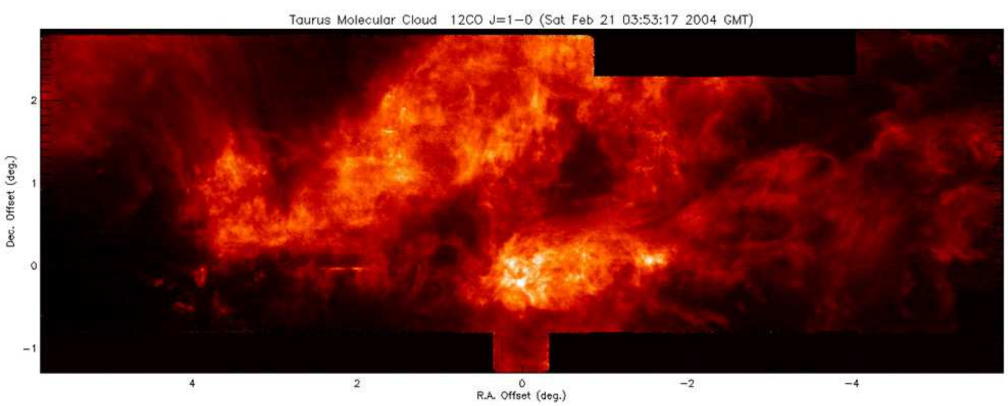


FIG. 1.—Velocity-integrated intensity of CO emission, W_{CO}. The lowest contour is 0.5 K km s^{-1}, and the separation between contours is 1.5 K km s^{-1}. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with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

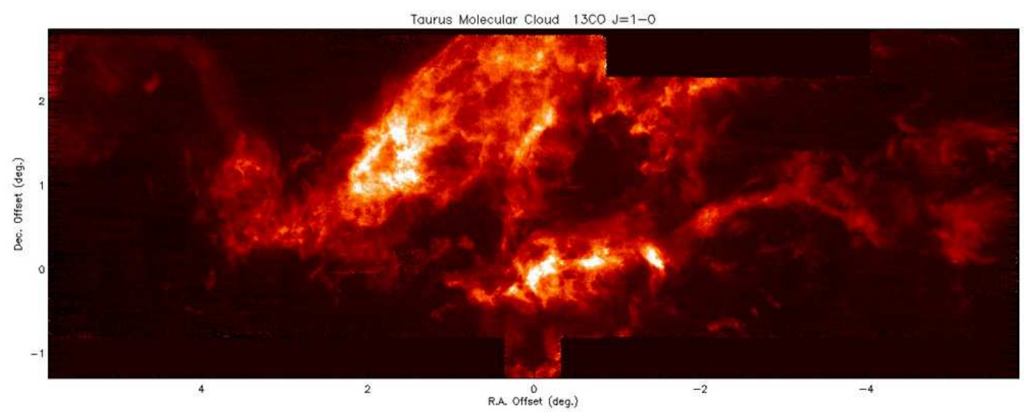
TMC in ^{12}CO



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

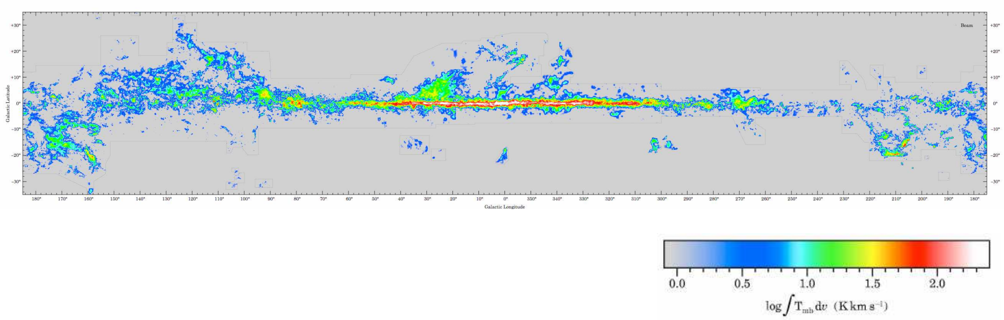
CO and HI

- 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 value is 2 to 3 × 10^{20} molecules cm^{-2} $(K\ \ km\ s^{-1})^{-1}$
  - Dame et al. 2001 value is 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

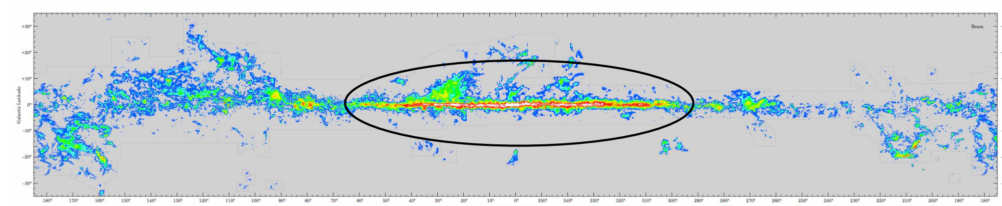
Distribution of Molecular Clouds

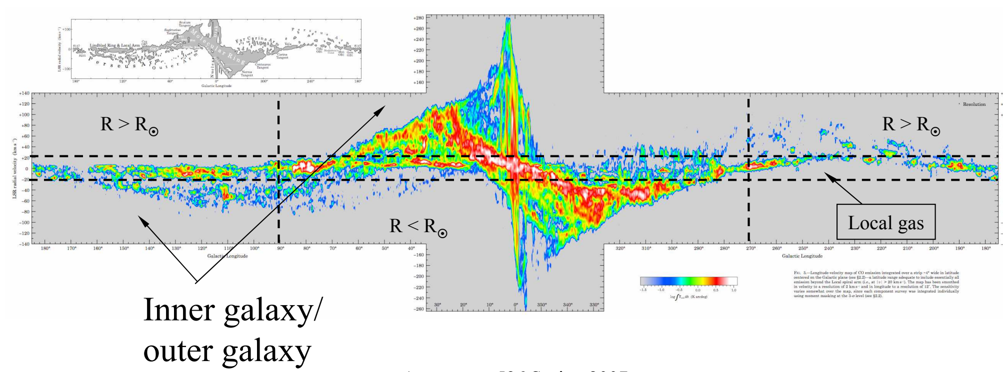


Dame et al. 2001: The CO distribution is plane of Galaxy is thin
- Vertical extent ±45-75 pc over much of the disk
- Similar to that of OB associations
- Flares out to ±100-200 pc

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

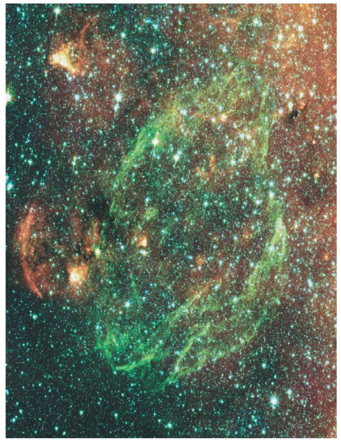
The Molecular Ring





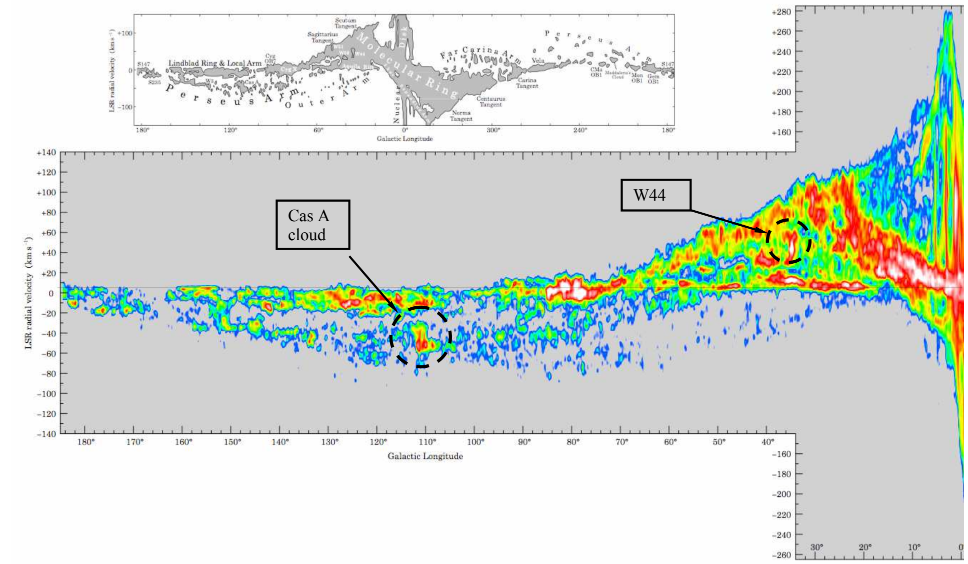
Giant Molecular Complexes

- 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
  - A large fraction 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

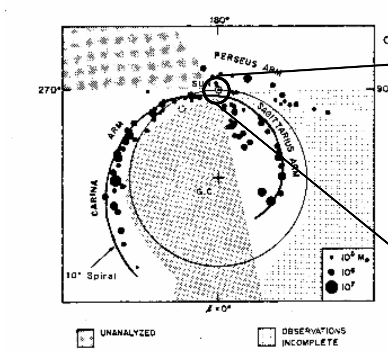


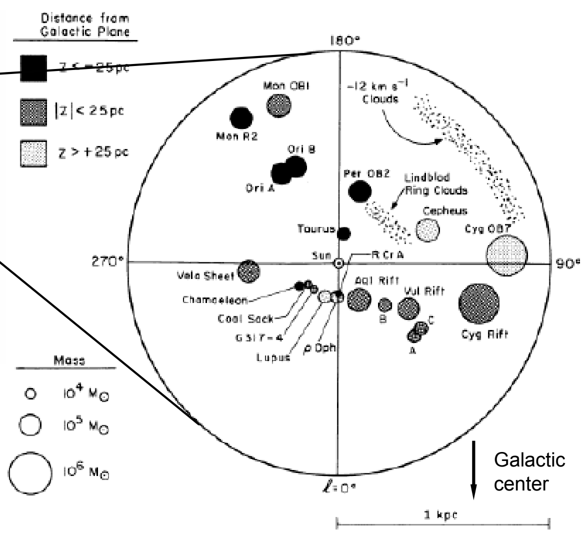
M44: Reach et al. 2006, ApJ, 131, 1479

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

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