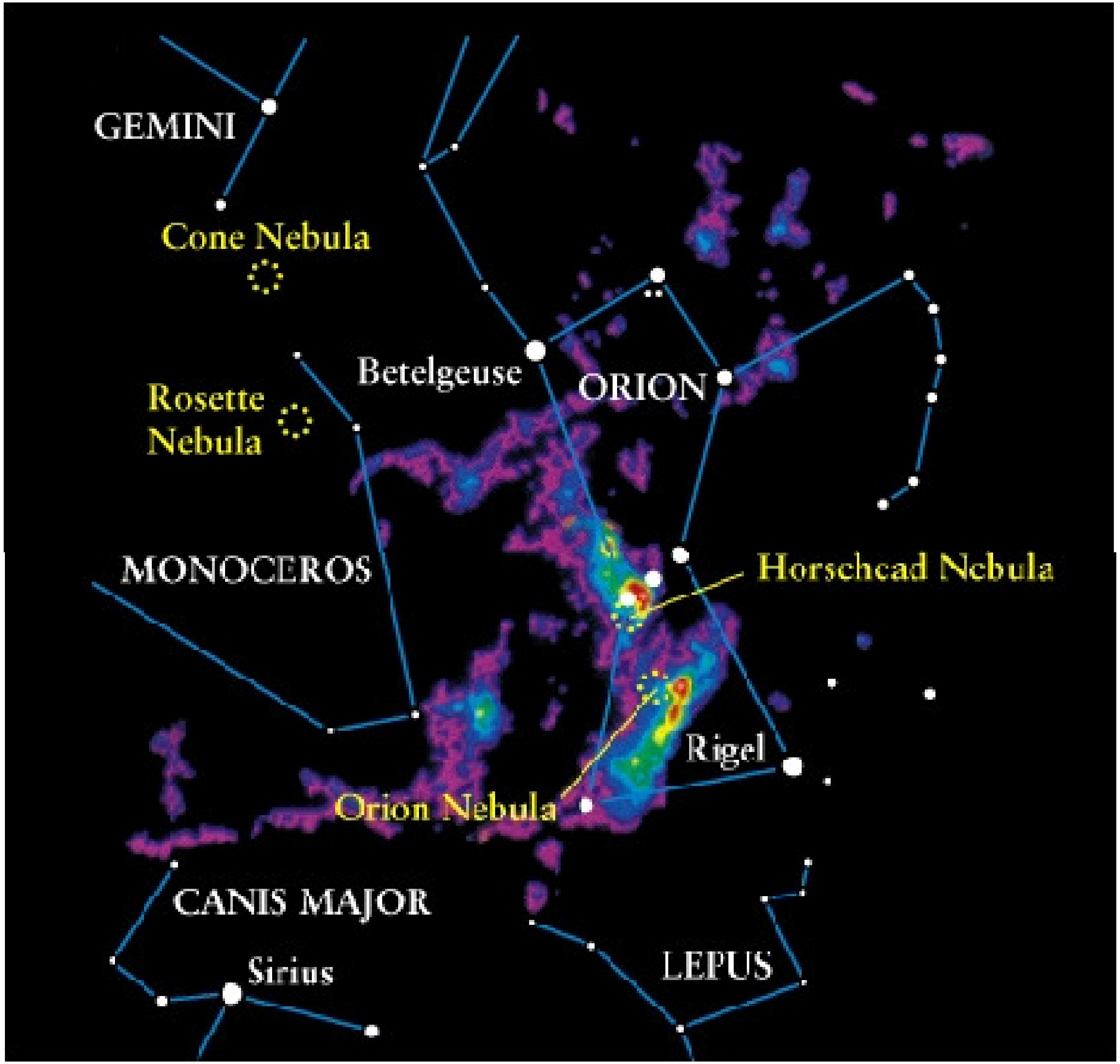
Molecular Clouds

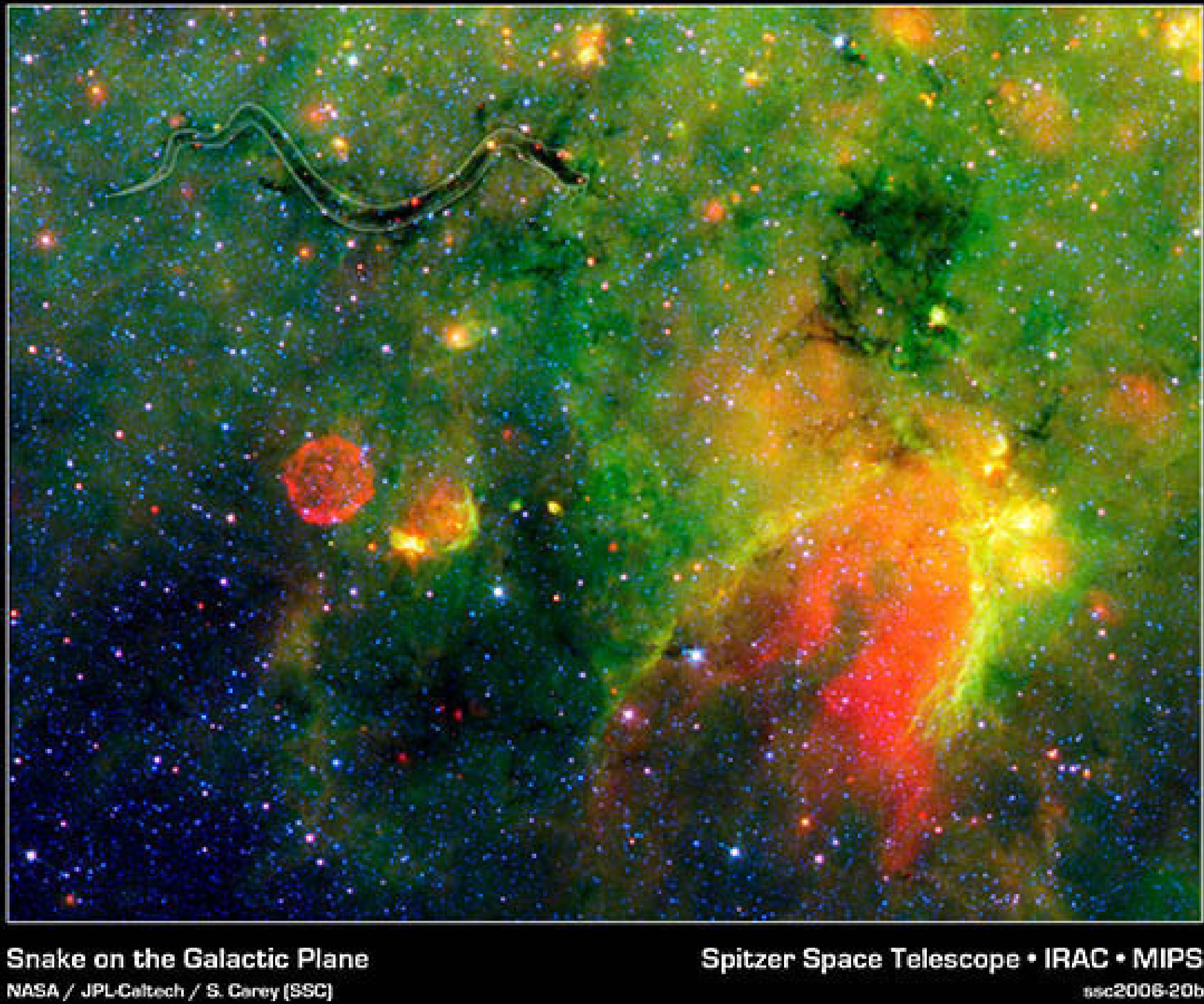
- **Molecular clouds are the densest and the coldest phases of the ISM**

- **In addition to H_2, the other molecular species found are CO, OH, NH_3, HCN, H_2O, aromatic hydrocarbons and many other organic molecules.**

- **Radio, millimeter and IR observations reveal the molecular composition of the ISM**

- **Star formation happens within molecular clouds**


GEMINI
Cone Nebula
Rosette Nebula
Betelgeuse
ORION
MONOCEROS
Horsehead Nebula
Rigel
Orion Nebula
CANIS MAJOR
Sirius
LEPUS



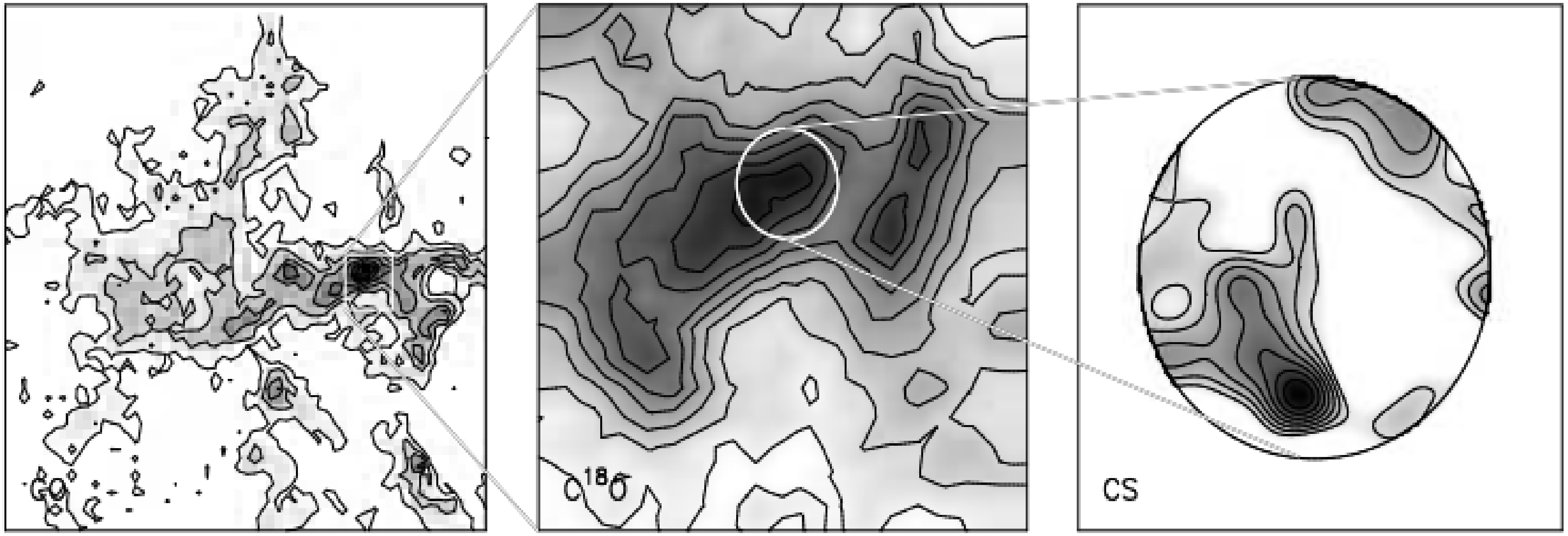
Spitzer image of IRDCG11.11-0.11, a molecular cloud in the Galaxy. Blue represents 3.6-micron light; green shows light of 8 micron; and red is 24-micron light.

Hierarchical Sub-structure in a molecular cloud

Terminology for Cloud Complexes and Their Components

Categories	Size (pc)	n_{H} (cm^{-3})	Mass ($M_{\odot}$)	Linewidth ($\mathrm{km\,s}^{-1}$)	A_V (mag)	Examples
GMC Complex	$25 - 200$	$50 - 300$	$10^5 - 10^{6.8}$	$4 - 17$	$3 - 10$	M17, W3, W51
Dark Cloud Complex	$4 - 25$	$10^2 - 10^3$	$10^3 - 10^{4.5}$	$1.5 - 5$	$4 - 12$	Taurus, Sco-Oph
GMC	$2 - 20$	$10^3 - 10^4$	$10^3 - 10^{5.3}$	$2 - 9$	$9 - 25$	Orion A, Orion B
Dark Cloud	$0.3 - 6$	$10^2 - 10^4$	$5 - 500$	$0.4 - 2$	$3 - 15$	B5, B227
Star-forming Clump	$0.2 - 2$	$10^4 - 10^5$	$10 - 10^3$	$0.5 - 3$	$4 - 90$	OMC-1, 2, 3, 4
Core	$0.02 - 0.4$	$10^4 - 10^6$	$0.3 - 10^2$	$0.3 - 2$	$30 - 200$	B335, L1535

Clouds, clumps & cores



Hierarchical cloud structure. The three panels show a representative view from cloud to clump to core. The bulk of the molecular gas (cloud; left panel) is best seen in CO which, although optically thick, faithfully outlines the location of the H_2. Internal structure (clumps; middle panel) is observed at higher resolution in an optically thin line such as $C^{18}O$. With a higher density tracer such as CS, cores (right panel) stand out. The observations here are of the Rosette molecular cloud and are respectively, Bell Labs (90″), FCRAO data (50″), and BIMA data (10″).

Blitz & Williams 1999 (astro-ph/9903382)

Spectra of Molecules

- **Astronomical spectra of molecules can come from three types of transitions :**

  (a) Rotational transitions : **long wavelengths ranging from radio for heavy polyatomic molecules, and** ***microwave (mm)*** **for lighter molecules**

  (b) Vibrational transitions : **at** ***sub-mm*** **and** ***far-infrared*** **wavelengths.**

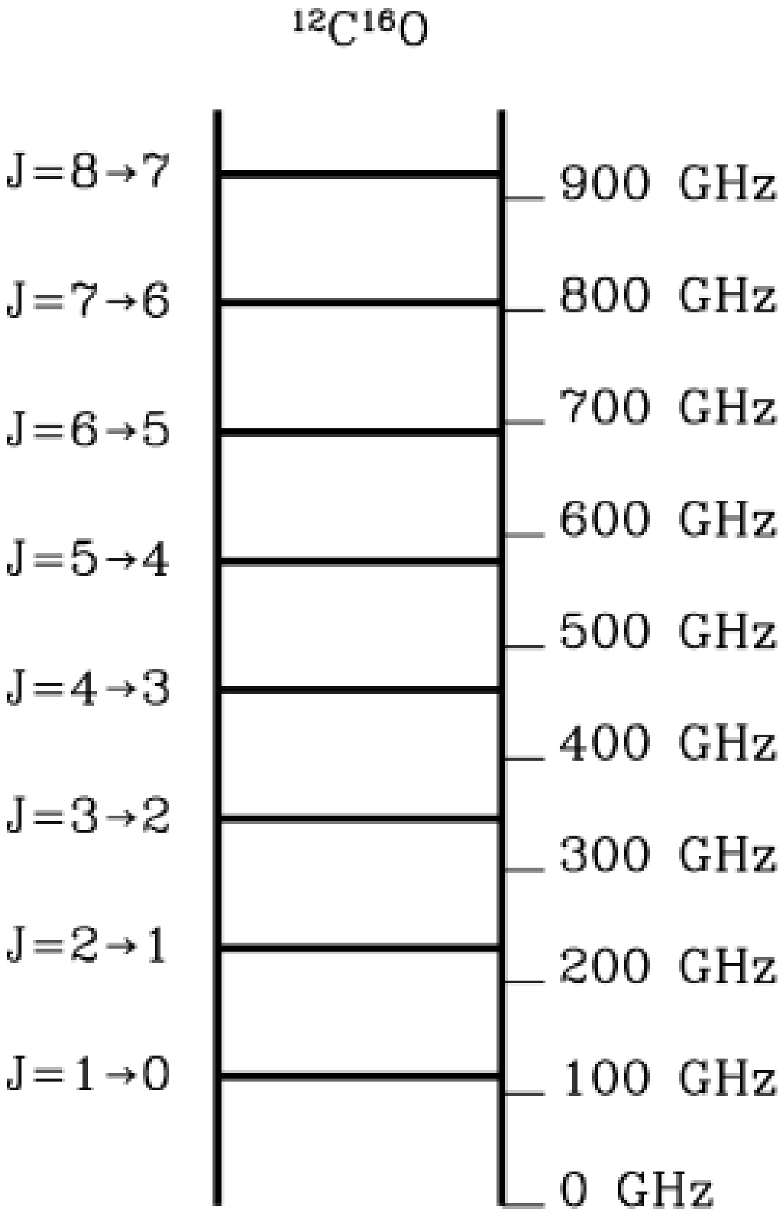
  (c) Electronic transitions : **lie at similar wavelengths to the allowed transitions of neutral atoms:** ***the visible and ultraviolet.***

Spectra of Molecules : *CO as a proxy for H_2*

- **H_2 is the most abundant molecule in the ISM, but cold H_2 is almost invisible to direct detection for the following reason :**

  H_2 has no asymmetry in charge distribution, hence no permanent electric dipole moment, and hence no rotational spectrum.

The lowest rotational transitions of H_2 are in at λ = 28.2 μm (far-IR) and shorter wavelengths. To detect these rotational transitions, H_2 molecule has to be excited. The excited rotational upper levels have energies of *E/k* ~ 510 K and 1015 K (*collisional excitation*). Similarly the lowest vibrational transition is at even higher energies of *E/k* ~ 6471 K. The cold ISM (molecular cloud) temperatures are lower than these excitation temperatures. Hence H_2 in emission is a weak signal.



$$\nu = \frac{\hbar J}{2\pi \mu r_e^2}$$

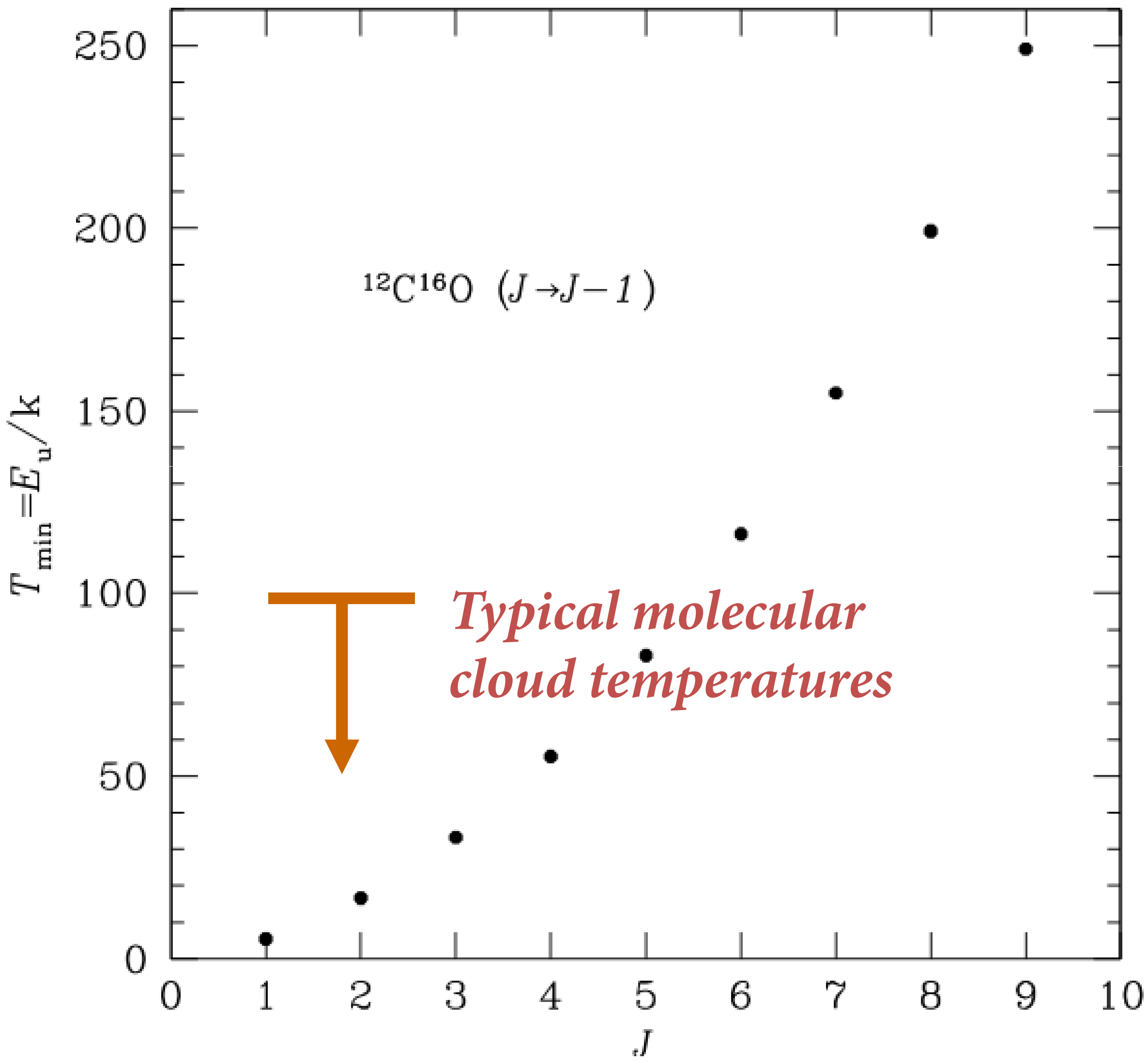
where J is the rotational angular momentum quantum number

The rotational spectrum of CO looks like a ladder whose rungs indicate the J levels and line frequencies. The CO molecule has a relatively small moment of inertia, so the lowest rung of this ladder is at 115 GHz (~ 2.6 cm).

Table 2.4 *Characteristics of molecular cooling lines*

Species	Transition	ν_{ul}(GHz)	E_u(K)	A_{ul} (s^{-1})	n_{cr} (cm^{-3})
CO	1–0	115.3	5.5	7.2×10^{-8}	1.1×10^{3}
	2–1	230.8	16.6	6.9×10^{-7}	6.7×10^{3}
	3–2	346.0	33.2	2.5×10^{-6}	2.1×10^{4}
	4–3	461.5	55.4	6.1×10^{-6}	4.4×10^{4}
	5–4	576.9	83.0	1.2×10^{-5}	7.8×10^{4}
	6–5	691.2	116.3	2.1×10^{-5}	1.3×10^{5}
	7–6	806.5	155.0	3.4×10^{-5}	2.0×10^{5}

Excitation Temperature for CO



The upper-level energies for CO J → J–1 transitions are proportional to J(J+1). The corresponding minimum temperatures required for collisions to excite the molecules are also proportional to J(J+1), so high-J lines will be weak in cold molecular clouds.

$$T_{min} \sim \frac{J(J+1)\hbar^2}{2Ik} \sim \frac{\nu h(J+1)}{2k}$$

Spectra of Molecules : *CO as a proxy for H_2*

- CO lowest rotational transitions are at excitation energies of E/k ~ 5.5 K, which is within the temperatures of cold molecular gas.

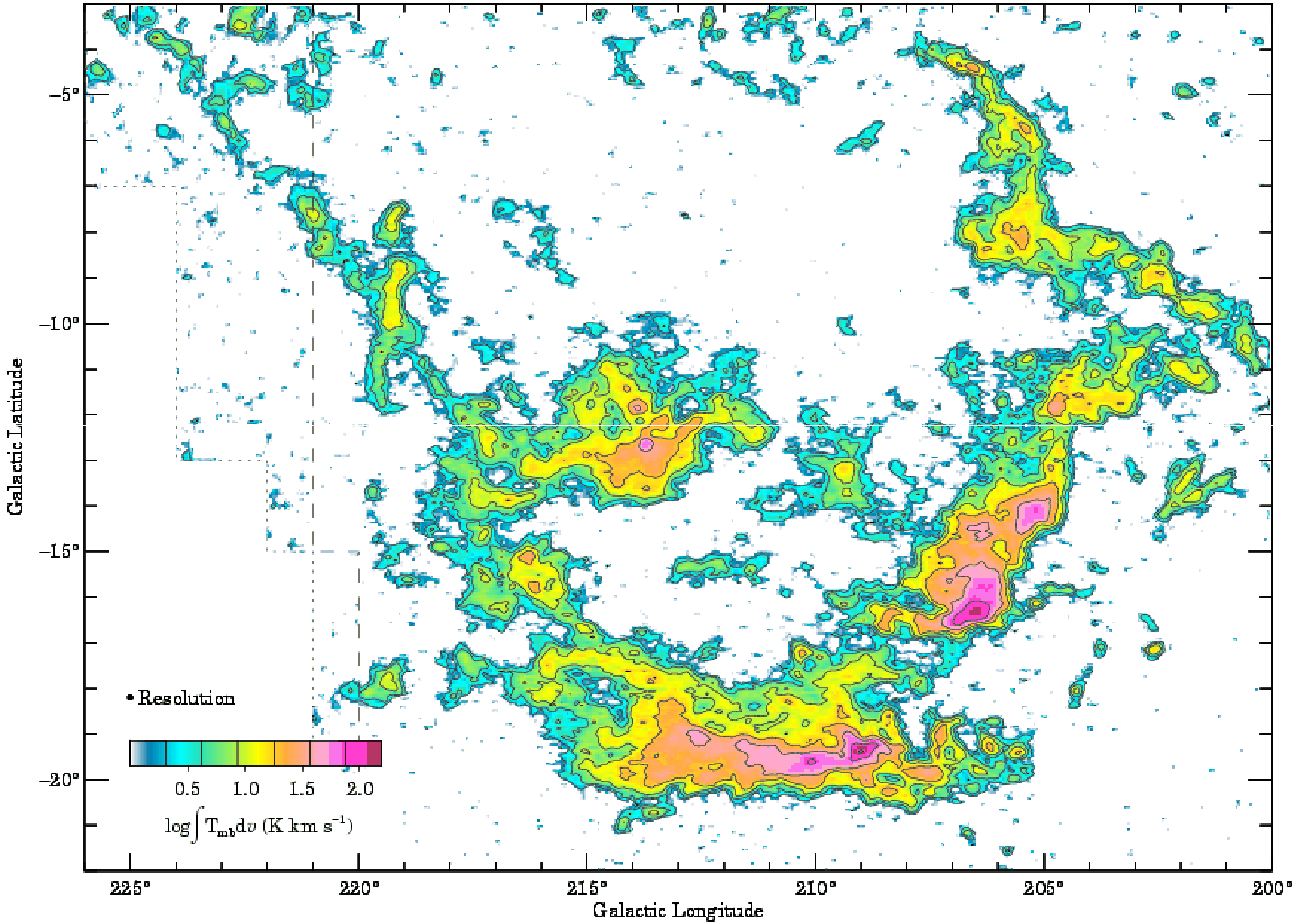
- CO rotational emissions at three prominent radio / mm frequencies are used to map the distribution of molecular gas in the Galaxy :

  (1) ^{12}CO (J = 1 → 0) @ 115.271203 GHz (2.6 mm – *atm window*)
  (2) ^{12}CO (J = 2 → 1) @ 230.538001 GHz
  (3) ^{13}CO (J = 1 → 0) @ 110.201370 GHz

- H_2 abundance in the ISM (i.e., molecular gas in the ISM) is estimated by converting the CO abundance into an H2 abundance : *weakest link in the estimation of molecular gas in the ISM*

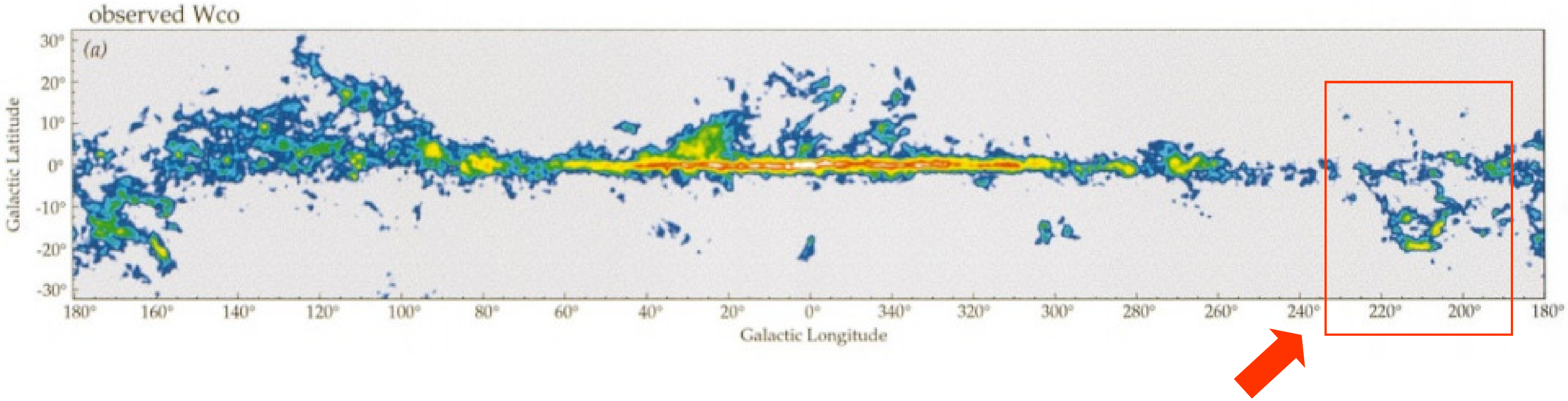
CO map @ 115 GHz of a molecular cloud region

(Orion-Monoceros star forming region)

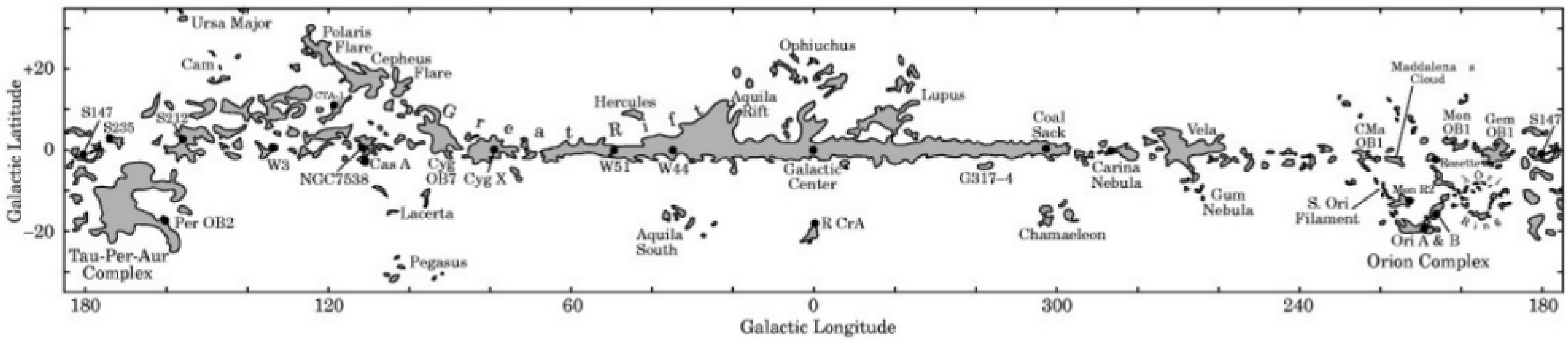


Wilson et al. 2005, A&A, 430, 523

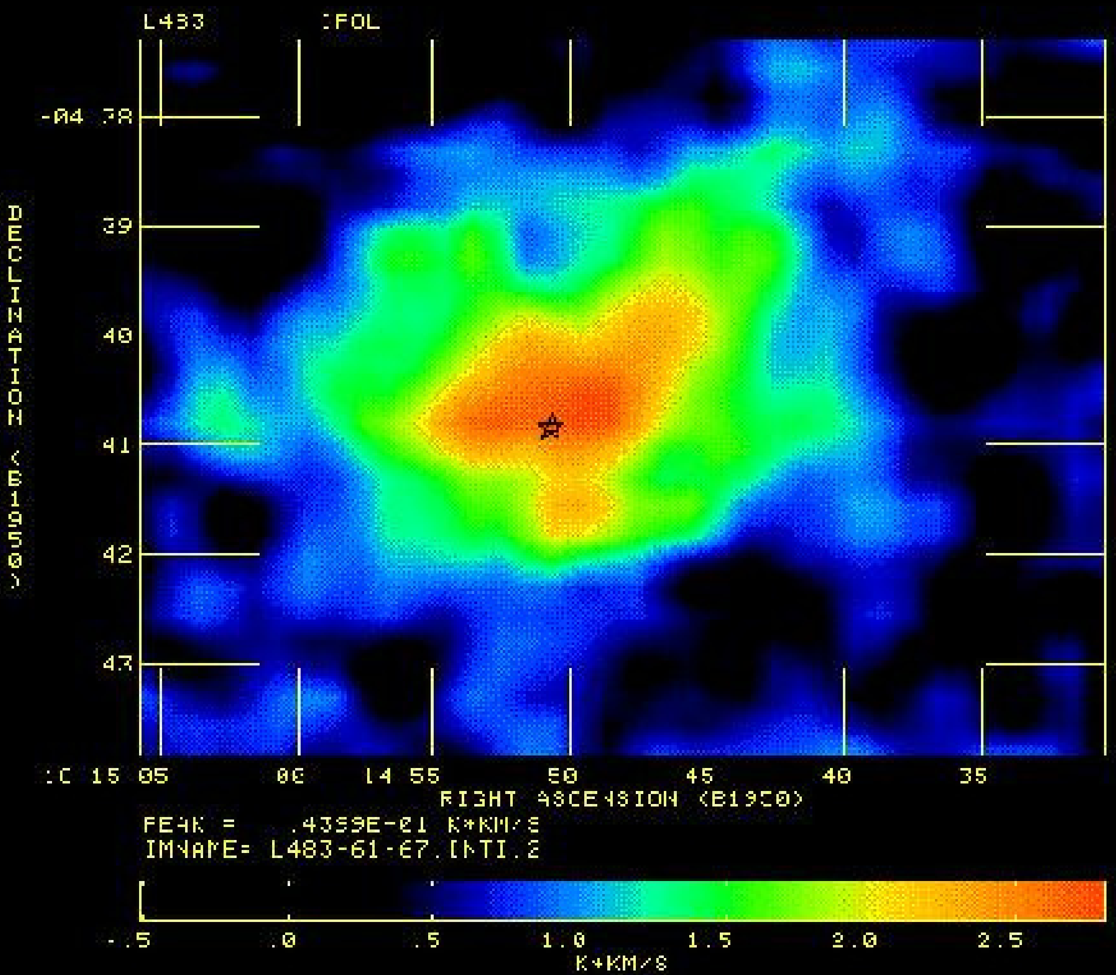
Distribution of H_2 (CO) in the Galaxy



Orion GMC



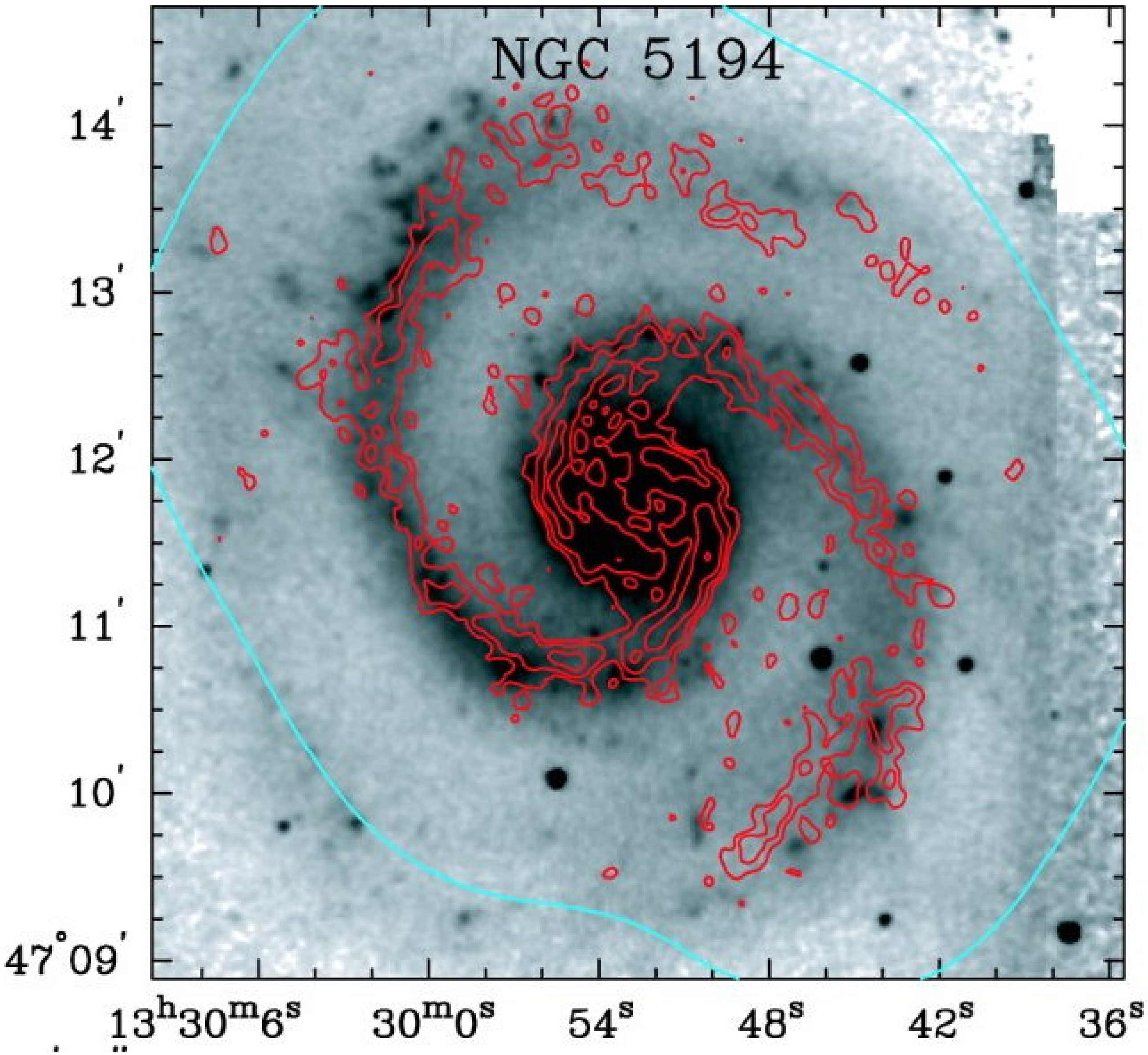
Examples of CO emission



Molecular cloud image taken by NRAO 12m radio telescope. Here the interstellar gas glows from the rotational emission of CO (J = 1 → 0) at 115 GHz. In the centre could be a protostellar core. The gas glows most brightly where accretion onto a protostar warms the cloud.

http://www.cv.nrao.edu/~awootten/research.html

Examples of CO emission



The CO J=1 - 0 contours superimposed on the optical image of the face-on spiral galaxy NGC 5194. The molecular emission traces the spiral arms and outline regions in which stars are forming. Strong CO emission is ubiquitous in star-forming galaxies.

(Regan, M. W. et al. 2001, ApJ, 561 218).