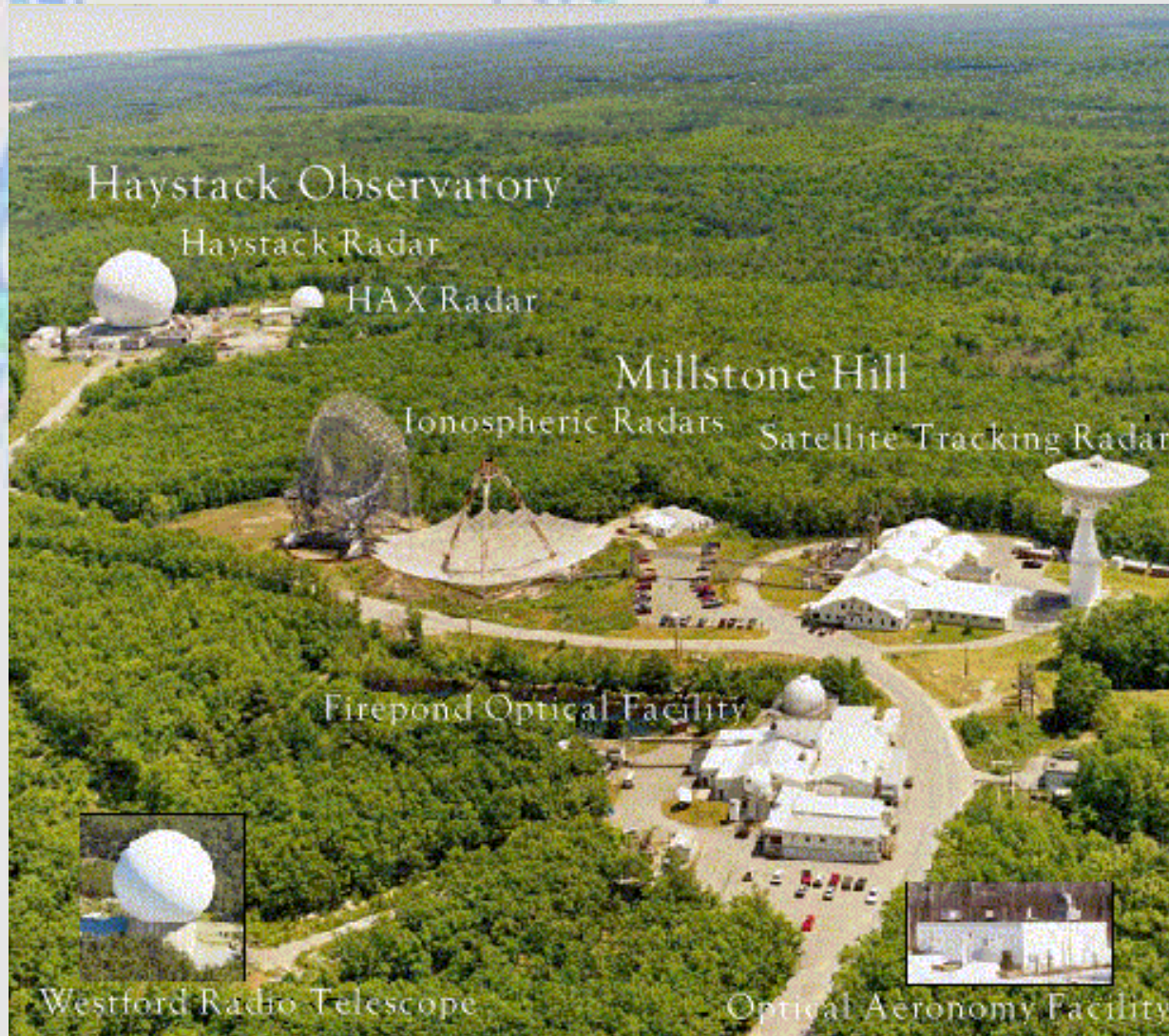


Molecular Lines in Radio Astronomy

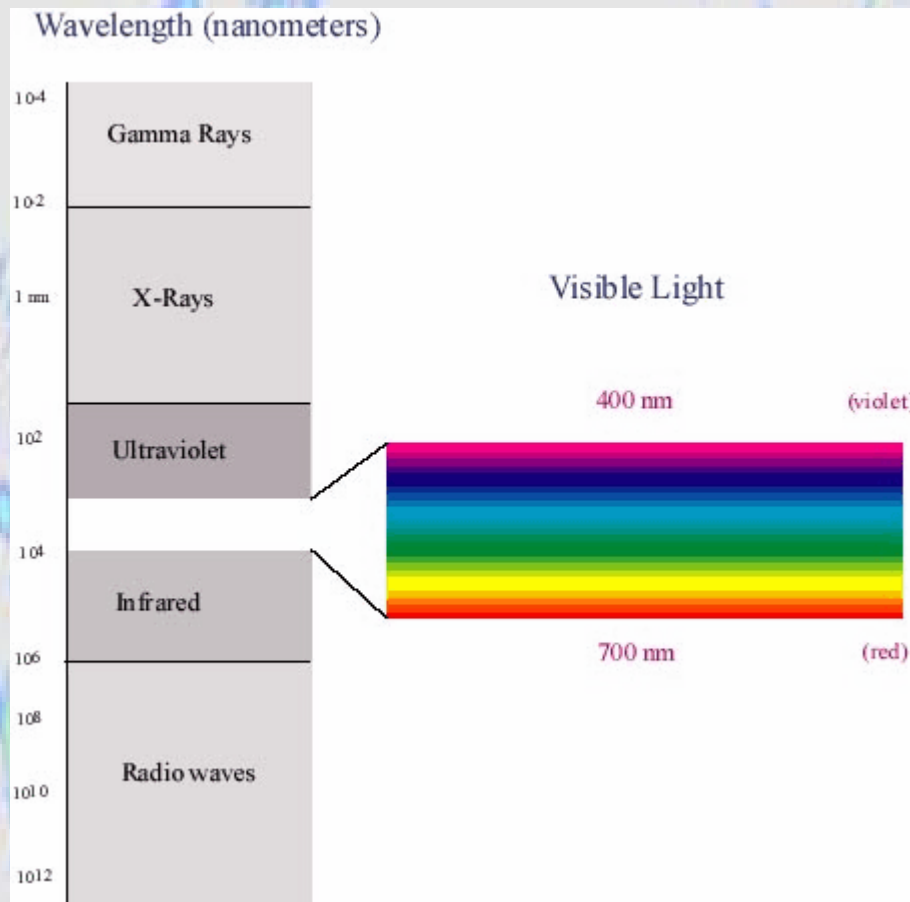
Preethi Pratap

MIT Haystack Observatory

MIT Haystack Observatory



The Electromagnetic Spectrum



Astronomical objects emit various kinds of radiation which are mostly related to the temperature and energy output of the source.

Radio waves are a large part of the EM spectrum and they are not stopped by the atmosphere

Molecular Rotation

Molecules need a non-zero dipole moment in order for the rotational energy state to change

Rotational energy for a linear molecule is given by:

$$W = h^2 J(J+1) / 8B^2I$$

where h is Planck's constant, W is the rotational energy, J is the angular momentum quantum number and I is the moment of inertia about the rotational axis

Frequency observed when molecule makes a transition between 2 rotational states:

$$L = W_2 - W_1 / h = 2B(J+1)$$

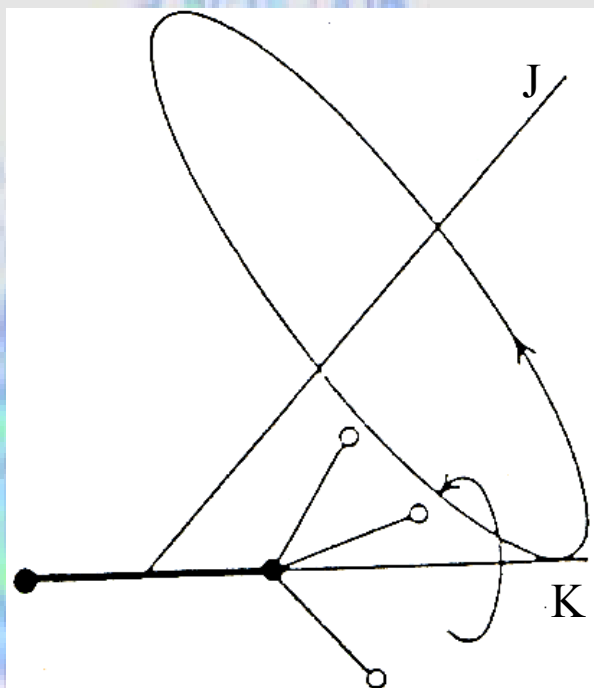
where $B = h^2 / 8B^2I$ is known as rotational constant

For Carbon Monoxide (CO), B has a value of 57897.5MHz, so the lowest rotational transition ($J=1-0$) has a frequency of roughly 115.8 GHz or a wavelength of 2.7mm which puts it in the radio part of the electromagnetic spectrum.

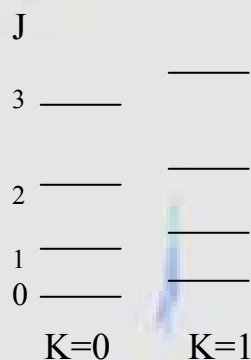
Symmetric top molecules

Molecules get more complicated - symmetric and asymmetric tops, interactions of nuclear charges with electric fields etc. all cause the spectrum to get more complex.

REFERENCE: *Molecular Spectroscopy by Townes and Schawlow*



Symmetric tops have equal moments of inertia about symmetry axis - characterized by quantum numbers J and K



Simple energy level diagram - K levels populated by collisions since radiative selection rules are limited to $\Delta K = 0$, relative populations between K ladders are governed only by collisions. So, symmetric top molecules are good probes of kinetic temperatures.

Interstellar Molecules

Simple Hydrides, Oxides, Sulfides, Haloids

H_2	CO	NH_3	CS	NaCl
HCl	SiO	SiH_4	SiS	AlCl
H_2O	SO_2	C_2	H_2S	KCl
	OCS	CH_4	PN	AlF

Nitriles, Acetylenes and Derivatives

C_3	HCN	CH_3CN	HNC	C_2H_4
C_5	HC_3N	CH_3C_3N	HNCO	C_2H_2
C_3O	HC_5N	CH_3C_5N	HNCS	CH_2CHCN
C_5O	HC_7N	CH_3C_4H	HNCCC	CH_3CH_2CN
C_3S	HC_9N	CH_3C_4H	CH_3NC	
C_4Si	$HC_{11}N$	C_2H_5CN	HCCNC	

Aldehydes, Alcohols, Aethers, Ketones and Amides

H_2CO	CH_3OH	HCOOH	CH_2NH	CH_2C_2
H_2CS	C_2H_5OH	CH_3COOH	CH_3NH_2	CH_2C_3
CH_3CHO	CH_3SH	$(CH_3)_2O$	NH_2CN	D_2CO
NH_2CHO		$(CH_3)_2CO$	H_2CCO	
$HCOOCH_3$	CH_2OHCHO			

Cyclic Molecules

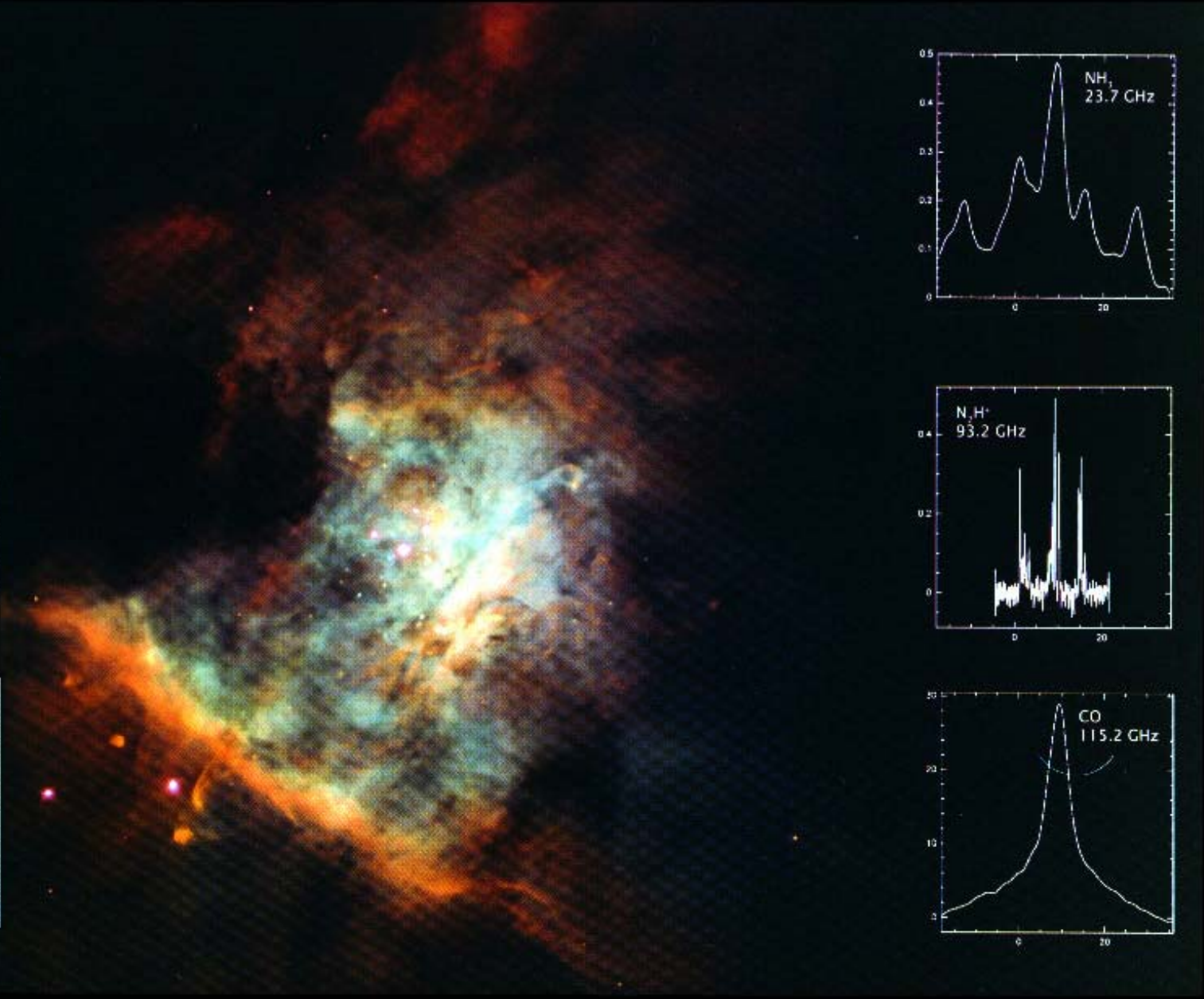
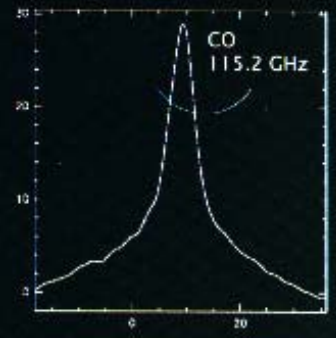
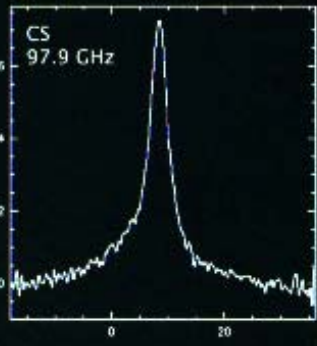
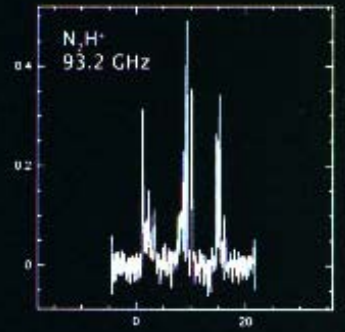
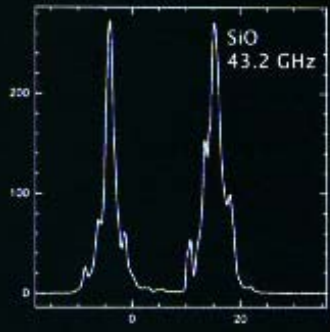
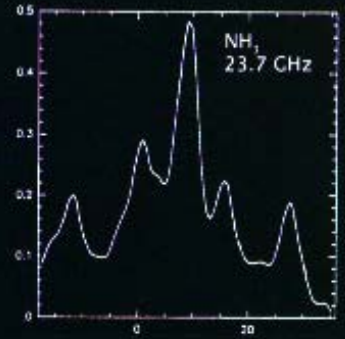
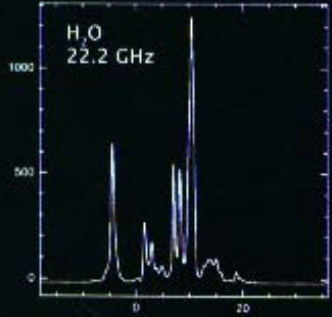
C_3H_2 SiC2 C-C3H

Molecular Ions

CH HCO^+ $HCNH^+$ H_3O^+
 HN_2^- HCS^+ $HOCO^+$ SO^+
 HOC^+ H_2D^- ND_2H^+

Radicals

OH C_3H CN C_2O C_2S
 CH C_4H C_3N NO NS
 C_2H C_5H HCCN SO SiC
 CH_2 C_6H CH_2CN HCO
 SiN NH MgNC CP

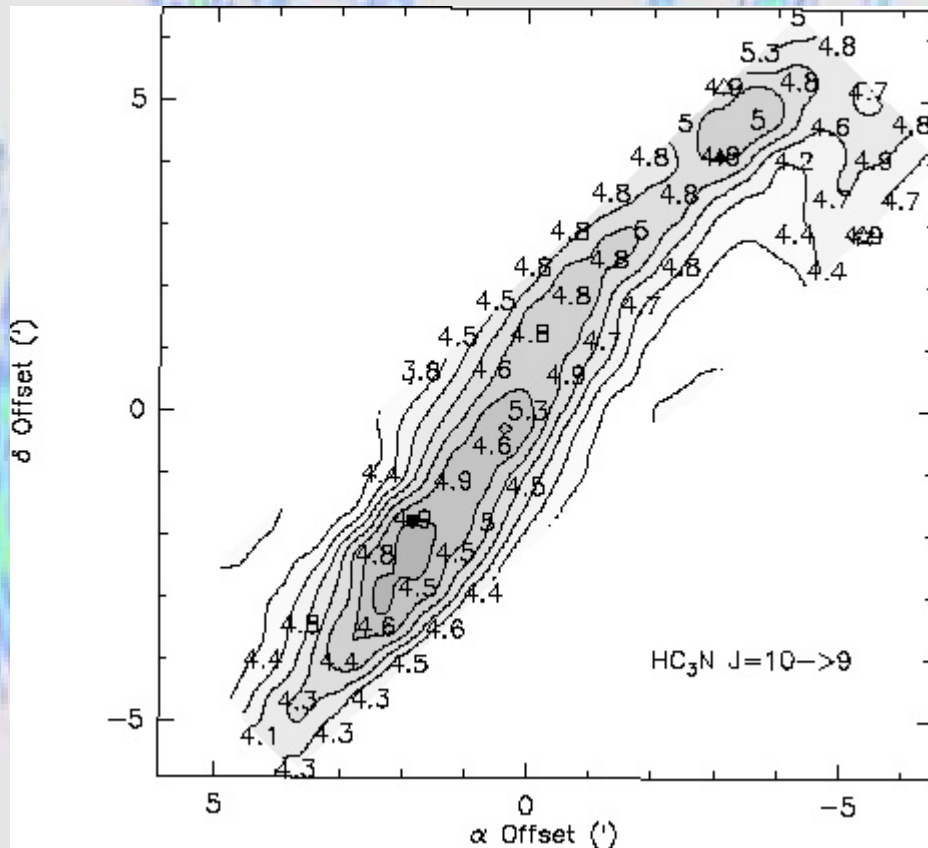
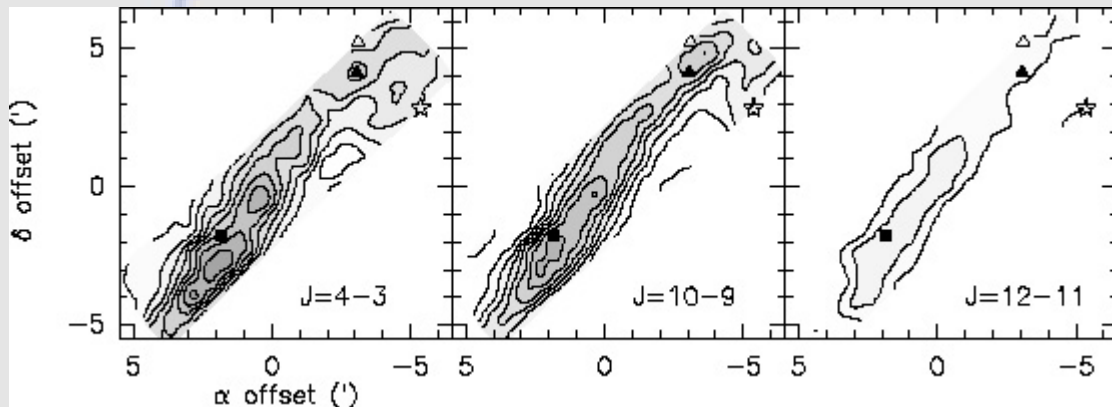


What are molecules good for?

- Detections - newest one - “glycoaldehyde” (sugar)
- Probes - measure temperature, density, chemistry
- Kinematics - velocities - doppler effect

Density Probes

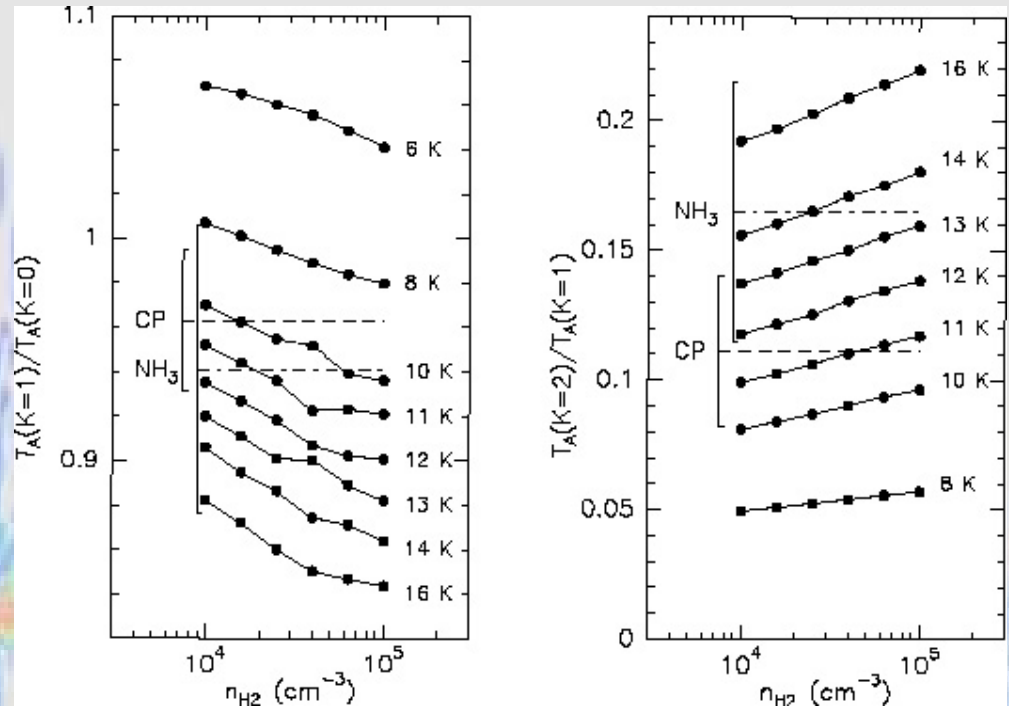
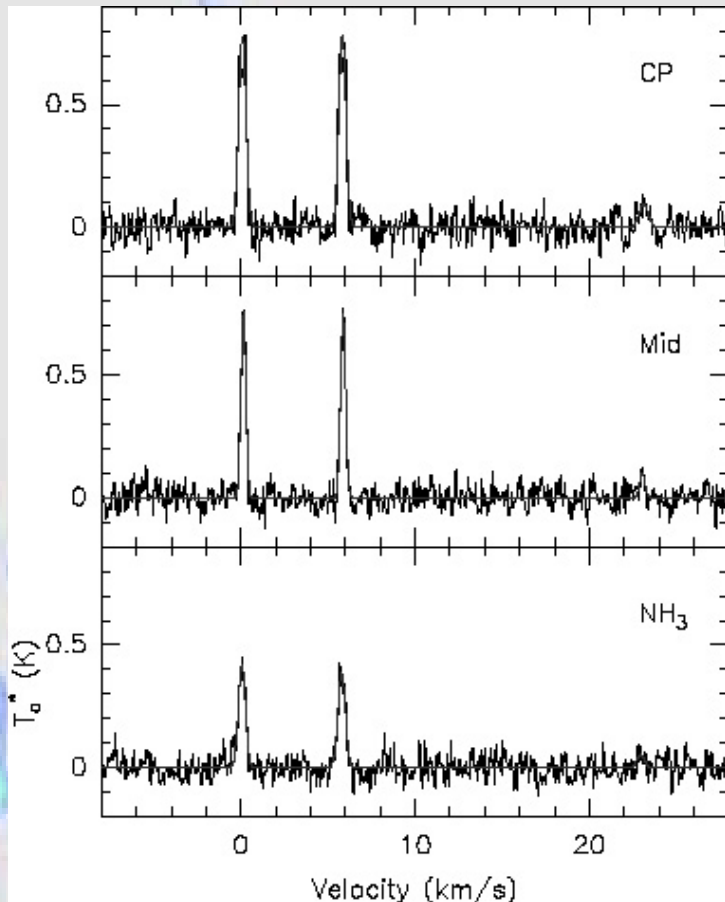
- Goal is to obtain H_2 densities
- Typical species used – CS, H_2CO , HC_3N
- CS, H_2CO more abundant
- HC_3N less abundant, higher dipole moment so probes denser regions
- Model the excitation of the energy levels and fit for the line intensities



Results from a density analysis of the HC_3N molecule toward a “dark” cloud – TMC-1.

Temperature probes

- Carbon monoxide - simple diatomic
- Emission everywhere
- Problems - optical depth effects saturate the line
- Symmetric top molecules

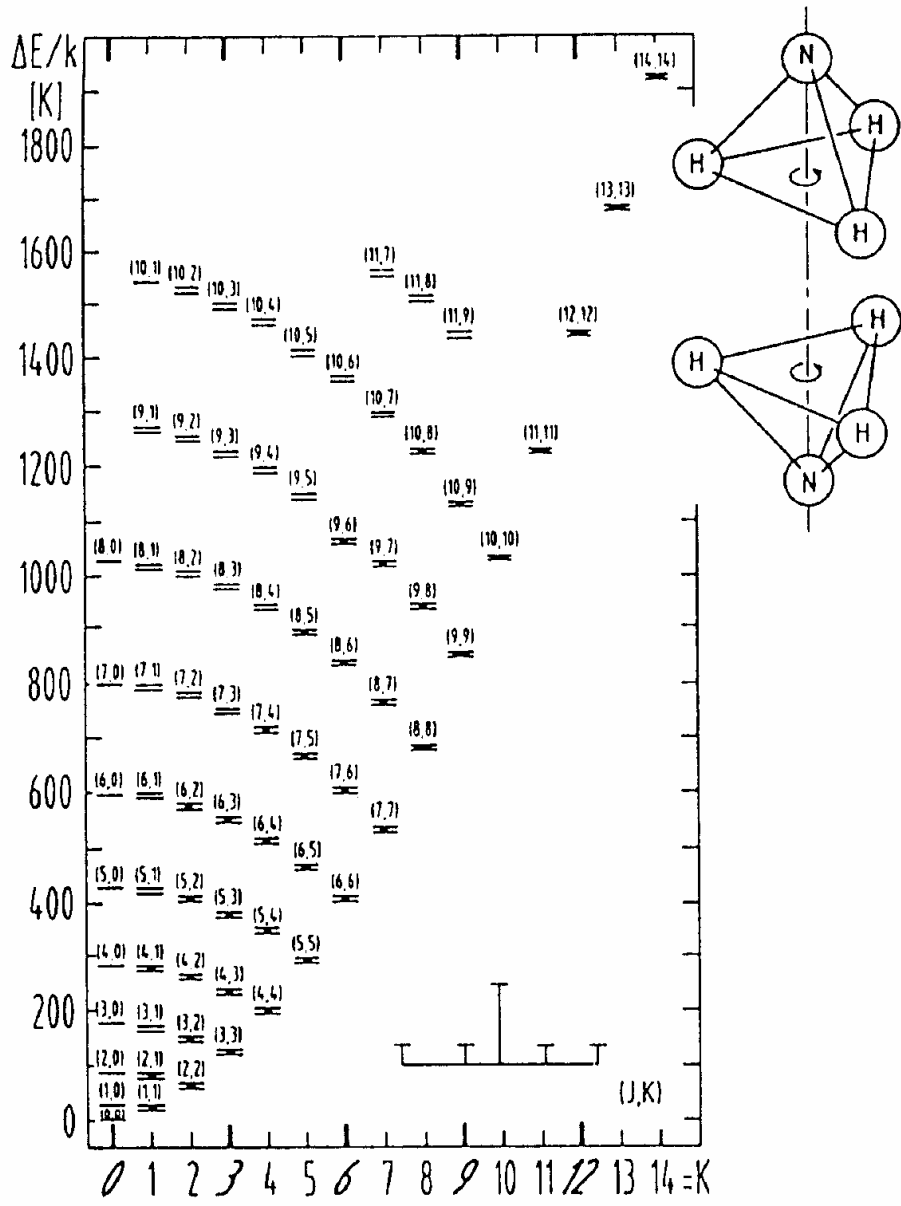


Spectra of CH_3CCH toward 3 positions in the TMC-1 molecular cloud

Results of a statistical equilibrium calculation of the CH_3CCH emission

Ammonia

- Symmetric top molecule with strong emission toward most molecular clouds
- Inversion transitions in the 1 cm range
- Hyperfine splitting provides measure of optical depths



Energy level diagram of ammonia. The splitting of the J levels is caused by inversion. Inset shows the pyramid shape of ammonia and the two configurations.

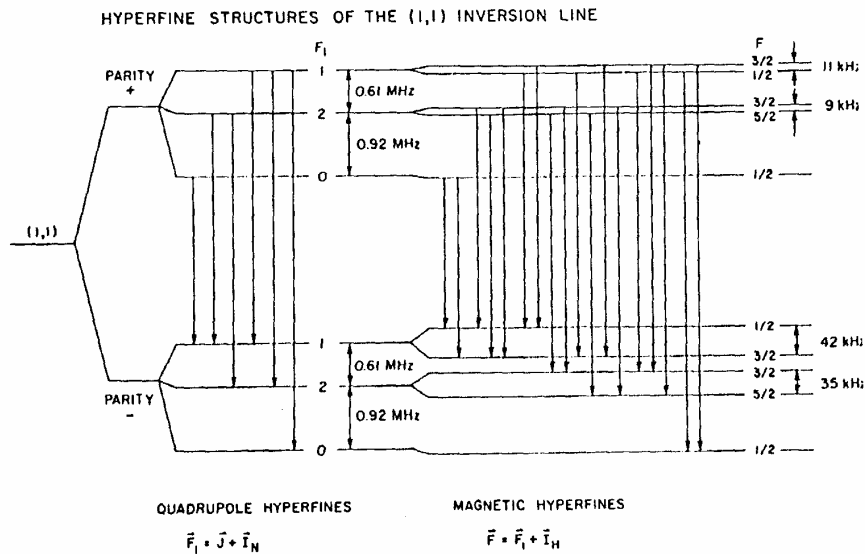


Figure 2 Hyperfine splitting of the $(J, K) = (1, 1)$ transition. The allowed transitions are indicated.

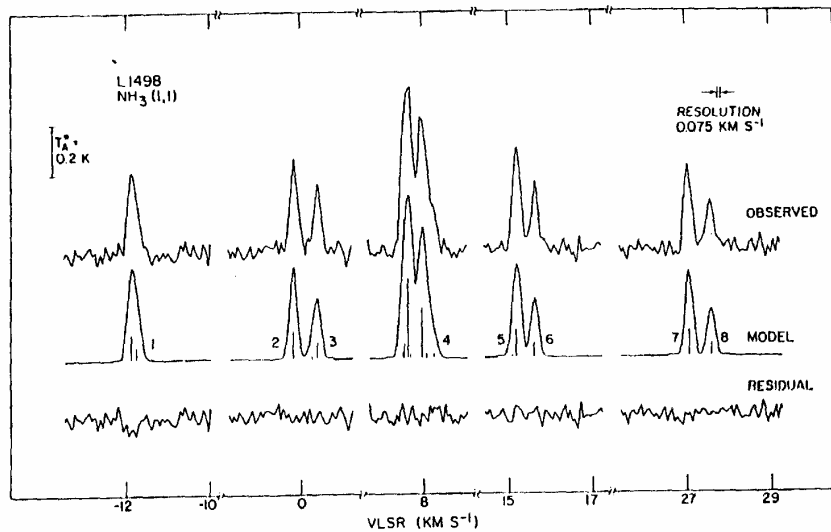


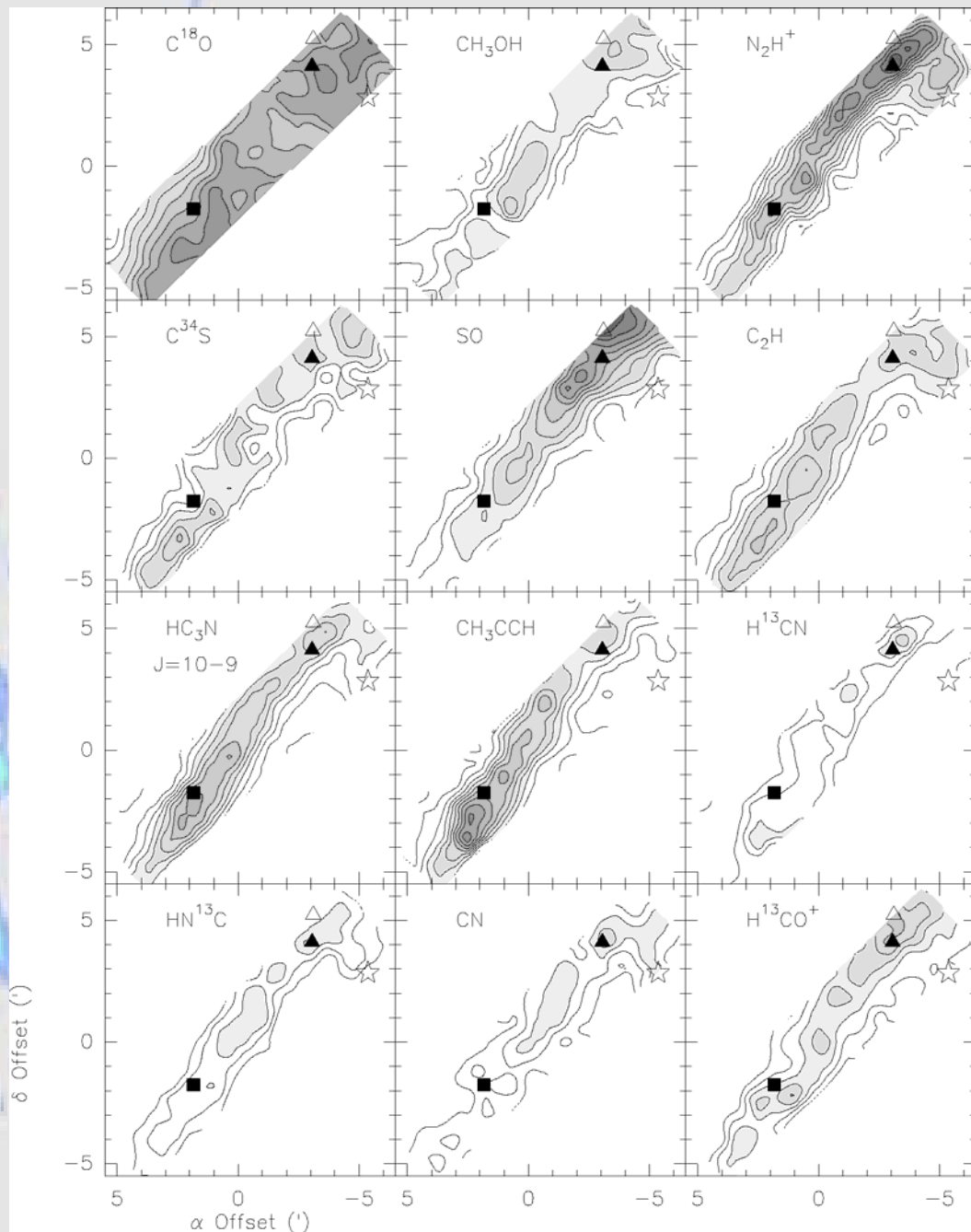
Figure 3 Observed $(J, K) = (1, 1)$ spectrum toward L1498 (Myers & Benson 1983). The relative LTE strengths of the various hyperfine components are indicated by the vertical tick marks under the model spectrum.

Hyperfine splitting of the $(J, K) = (1, 1)$ line of ammonia

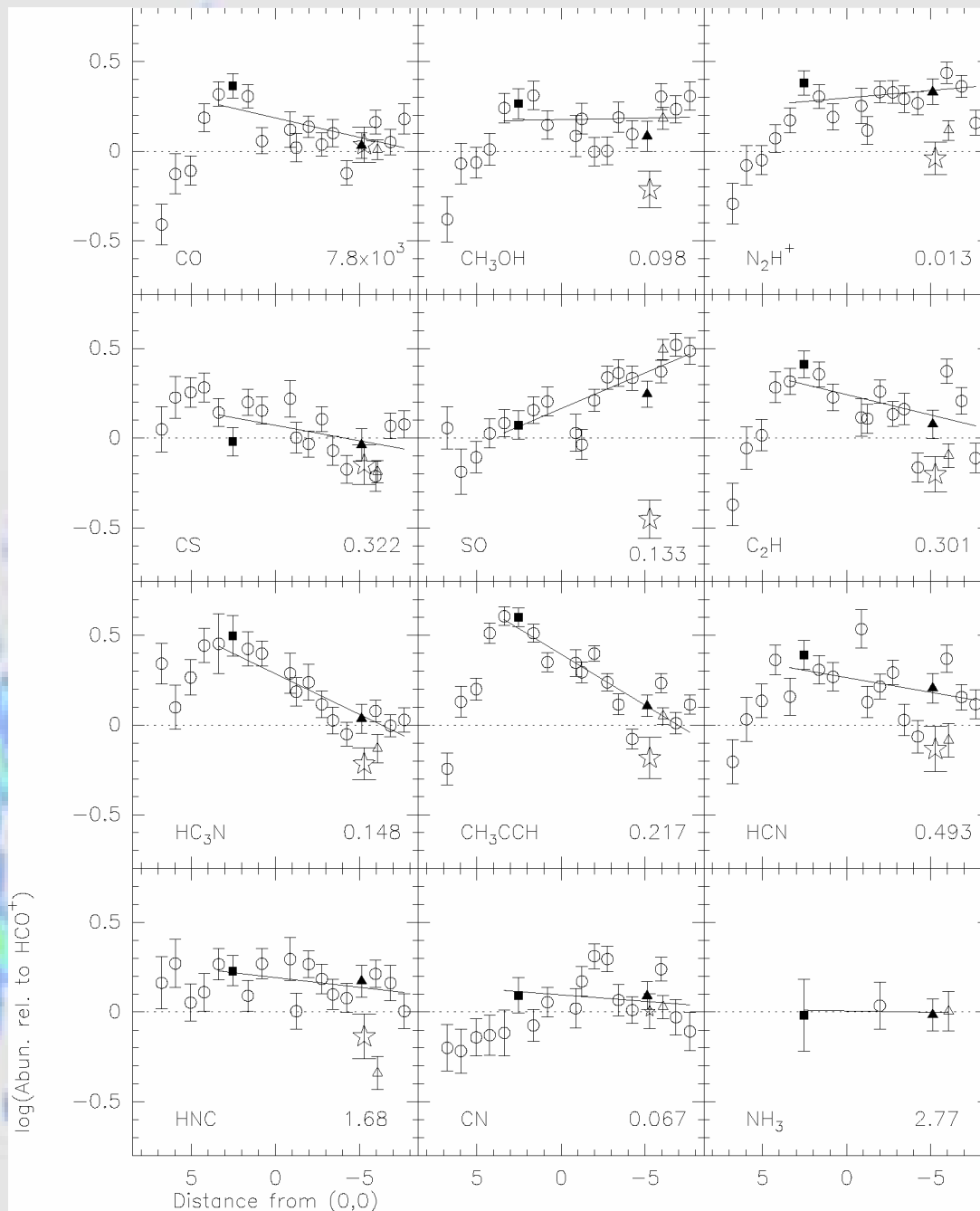
$(1, 1)$ spectrum of ammonia toward L1498 (a “dark” cloud). Bottom spectrum is a model.

Chemistry

- Emission strengths can be used to calculate molecular abundances
- Comparison of ratios of common species with predictions from chemical models can be useful in studying the chemistry in molecular clouds



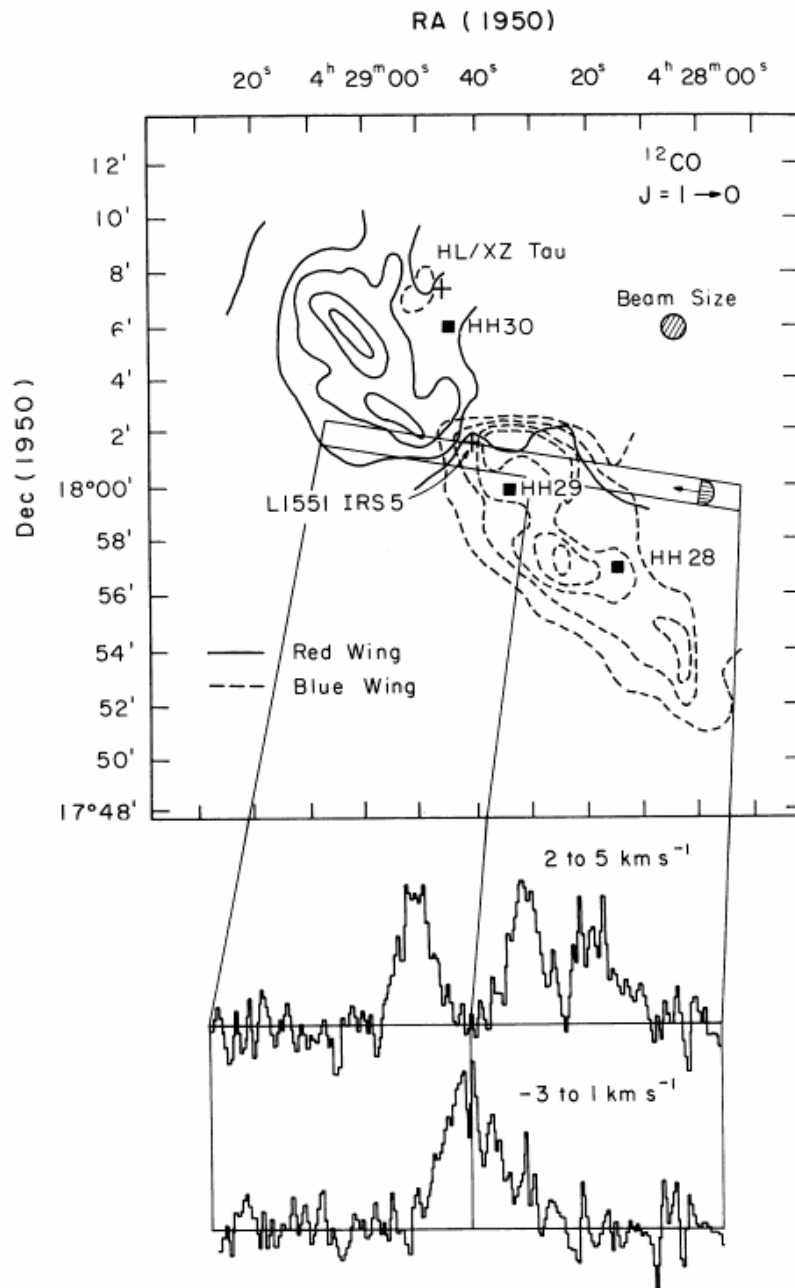
Integrated intensity
contour maps of several
molecular species
towards TMC-1.



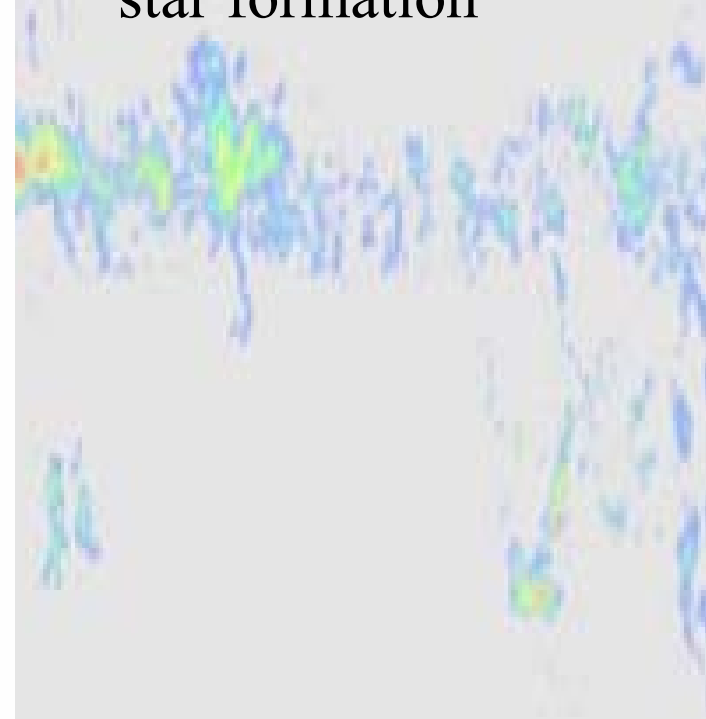
Model results for the TMC-1 study. The x-axes show the relative abundance of the species w.r.t HCO⁺ and the y-axis shows distance along the molecular ridge

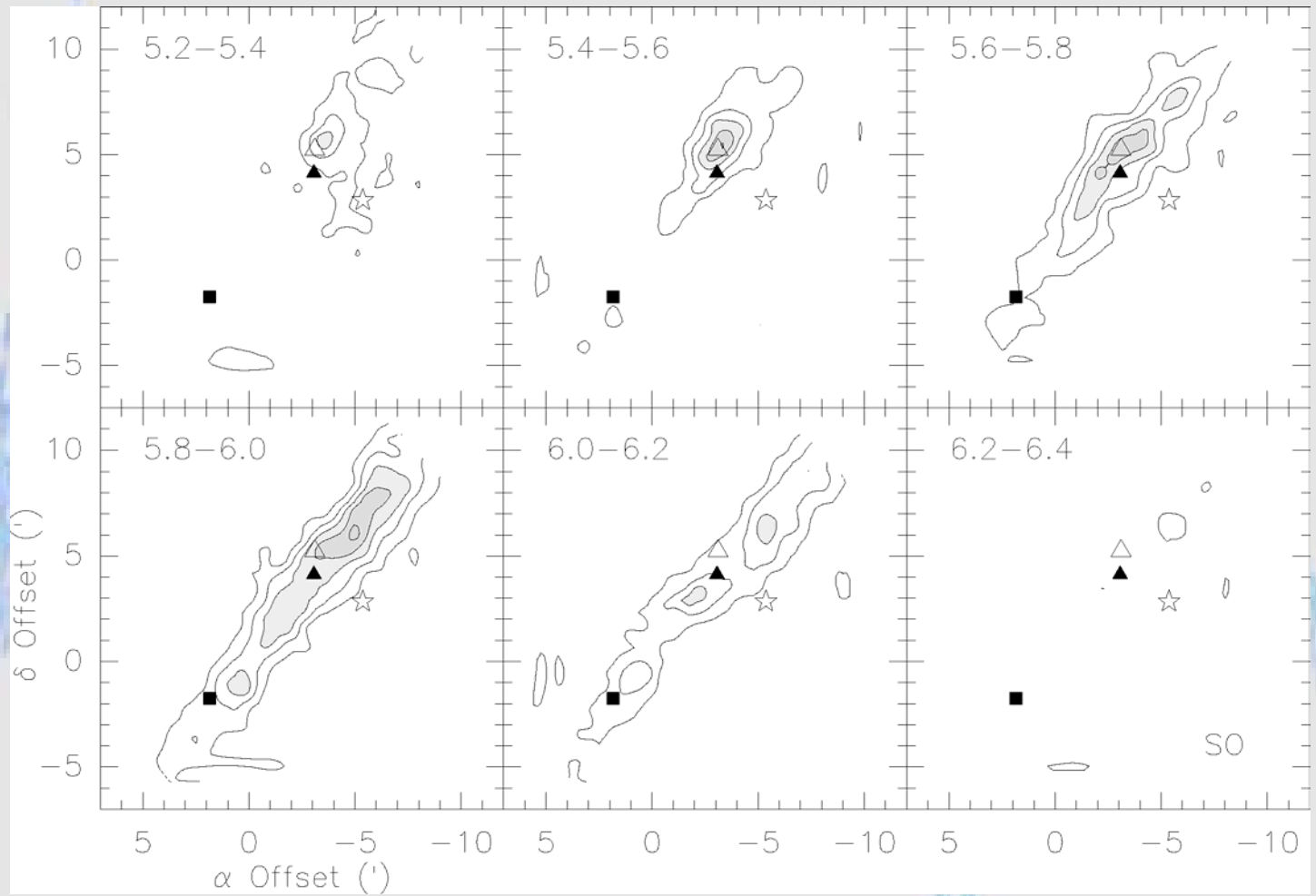
Kinematics

- Study of the line profiles of molecular lines can be used in kinematic studies
- Channel maps of sources can be used in detecting gas motions - commonly used to detect molecular outflows
- Maser emission can be used to trace small scale kinematic motions



Map of the red and blue wings of the CO emission toward L1551 - a site of star formation





Maps of SO emission toward the TMC-1 ridge. The numbers on the top left corner indicate velocity intervals.

Masers

Microwave Amplification by Stimulated Emission of Radiation

Masers occur by *population inversion* - number of molecules in higher energy state exceed those in lower energy state - when it encounters a photon of appropriate energy it responds by emitting a photon - resulting in a cascade

Masers are very intense and highly beamed

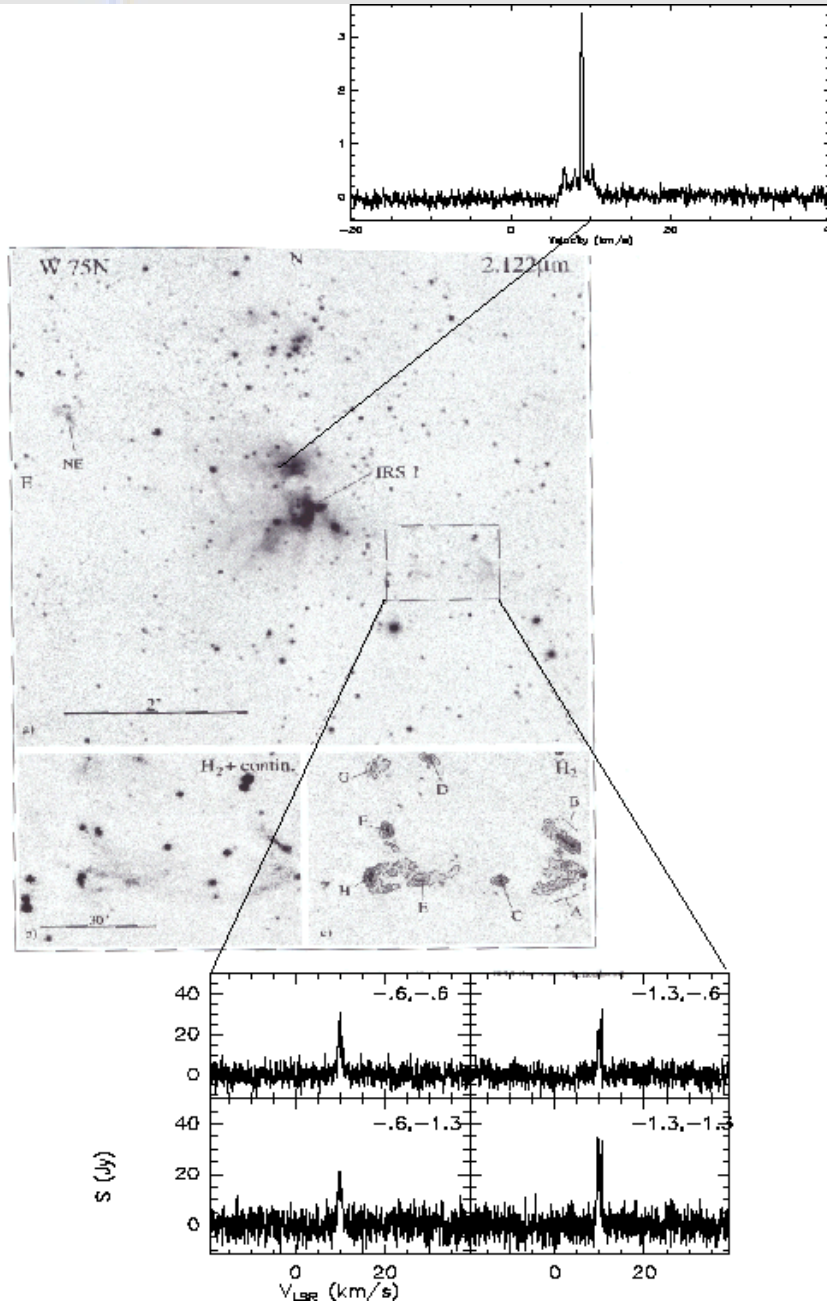
Molecules that have shown maser action include - Water, OH, methanol, SiO, Ammonia, Formaldehyde and even the hydrogen atom.

Methanol Maser Survey

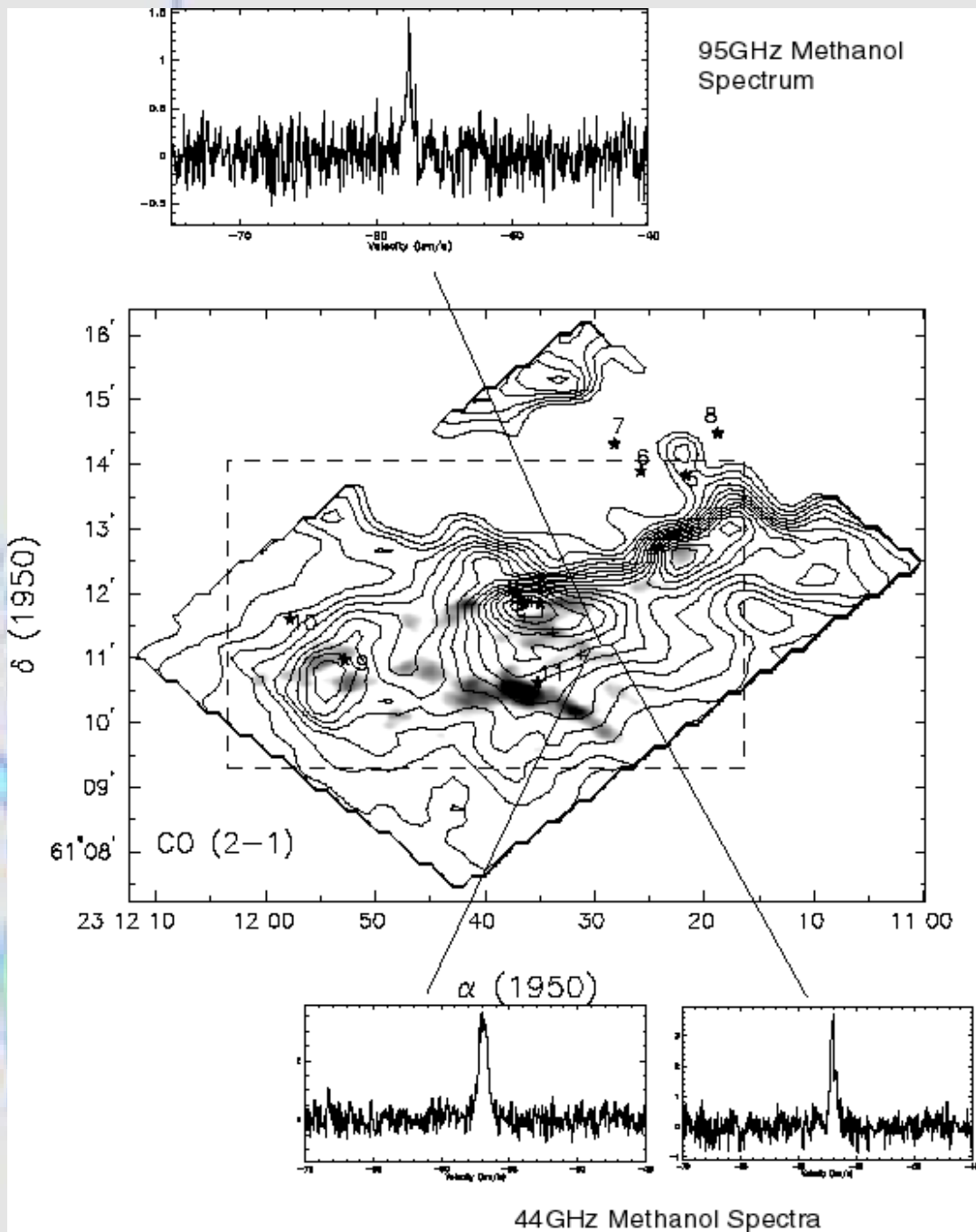
- Are Class I methanol masers always associated with outflow activity? If so are they found at the interfaces between the outflows and the molecular material or in the disks around the young stars?

Are Class I masers a tracer of a very early stage of star formation? If so they could prove to be invaluable in detecting new star formation sites.

- Several clouds have been observed
 - W3OH - Carrie Perkowski, Mt. Union College
 - Cepheus - Rudy Montez, Univ. of Texas
 - W75N - Christian Clerc, Univ. of Dallas
 - OMC-2 - Dan Brubaker, College of Wooster
 - NGC 7538 - started by Cara Misserville, U. of Mass.
 - S255 - Wellesley College undergraduate students
 - S140 - Kris Barkume, Reed College



**Methanol spectra toward W75N showing emission toward an H₂ bow shock region (previously unknown)
 Data taken by Christian Clerc (sophomore at the Univ. of Dallas and REU student at College of Wooster)**



Methanol spectra toward NGC 7538 - a star forming region - peak of the spectrum is offset by over 1' from star formation sites - project was started by Cara Misserville (Univ of Mass. Lowell)

Bio Molecules

Complex and saturated molecules including those of biological significance have been found exclusively in hot molecular cores

Cores are usually associated with centers of early star formation

Complex chemical processes which include chemistry on grain surfaces have to be invoked to explain the presence of these molecules

Formic acid (one example) - simplest organic acid - shares common structural elements with methyl formate, acetic acid and glycine which are biologically significant .

It has been detected in a variety of environments including massive star forming regions, dark molecular clouds and Comet Hale-Bopp