Lecture 21
Distribution of the Molecular Gas

1. Global Distribution of Gas
2. Atomic Hydrogen and GMCs
3. Formation
4. Internal Structure
5. Observing Molecular Cloud Cores

References

Origins of Stars & Planetary Systems

http://www.cfa.harvard.edu/events/1999crete

Myers, “Physical Conditions in Molecular Clouds”

Blitz & Williams, “Molecular Clouds”

Lada, “The Formation of Low-Mass Stars”

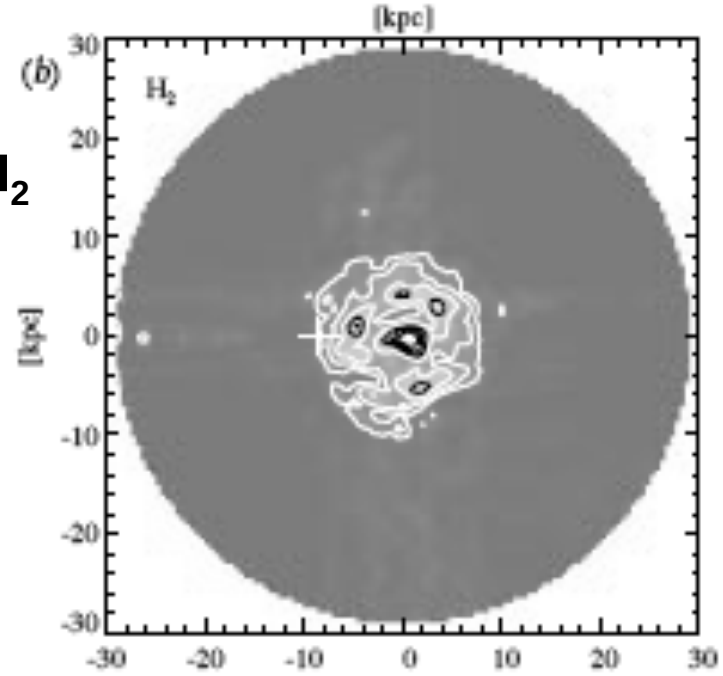
1. Global Distribution of Molecular Gas

- Observing from inside makes it difficult to sort out the distribution of molecular gas in the Milky Way.
- The CO emission is inhomogeneous (radially and azimuthally).
- Confusion and kinematic ambiguity make it difficult to determine whether GMCs are primarily located in spiral arms.
- The X-factor is used to obtain the H_2 surface density.
- H_2 has a ring ("5-kpc ring") with a hole at the center (next slide).
- Higher angular resolution and observations of external galaxies are particularly useful.
- The total H_2 and HI masses are of he same order, but the ratio is highly variable

HI and H2 Column Densities

Hunter et al. ApJ 2001

H_2



HI

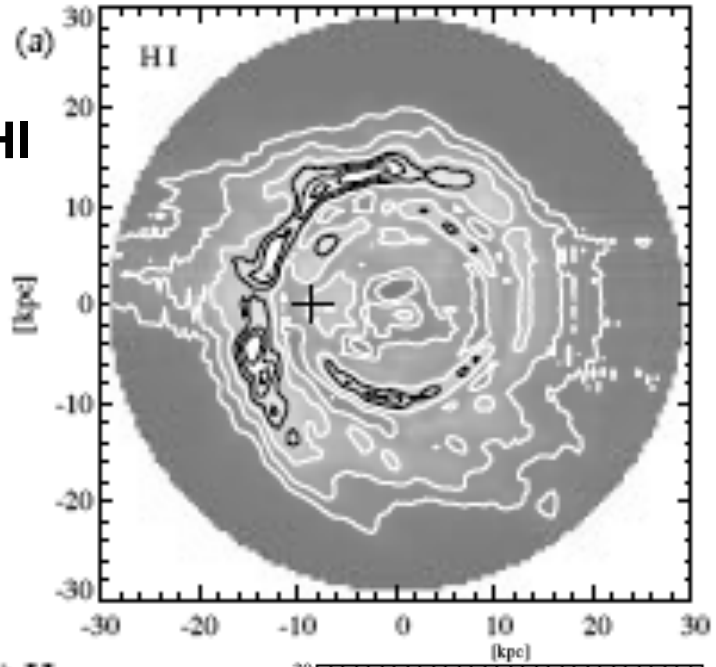
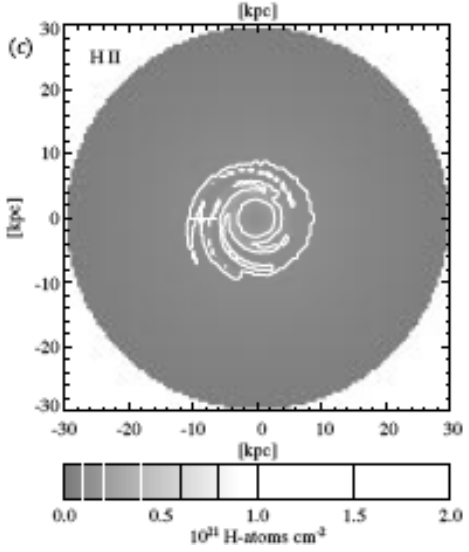


FIG. 8.—Total surface densities of (*a*) H I, (*b*) H_2, and (*c*) H II as a function of position in the Galactic plane. The H I and H_2 plots have been smoothed to 2 kpc resolution. The position of the Sun is indicated with a cross. The gas densities are assumed to be zero beyond the 30 kpc Galactic radius limit of the calculation (see § 5).

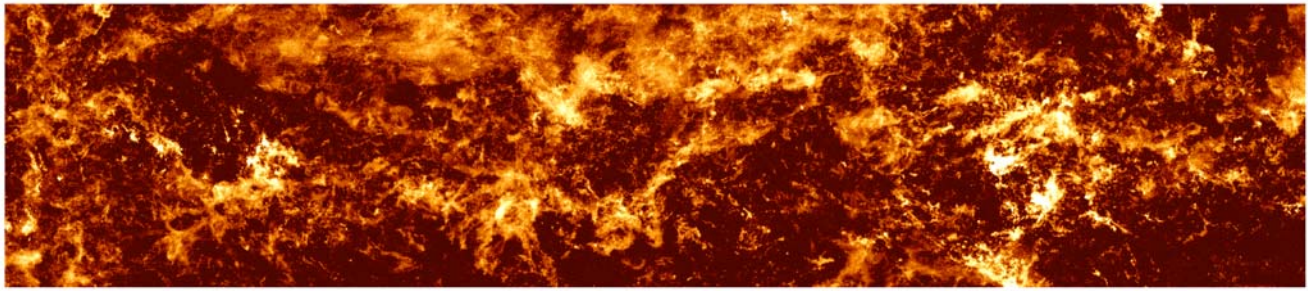
HII



- Modeling of γ-rays and CfA CO survey
- H_2 has a ring with a hole at the center
- Spiral arms are not delineated clearly

FCRAO Outer Galaxy Survey

Heyer et al. ApJS 115 241 1998



- **Regions of little molecular gas**, perhaps cleared by photodissociation, stellar winds and supernova from massive stars. The last two processes can sweep up and compress gas and help make new stars.
- **CO is primarily in spiral arms,** with estimated H_2 *arm-interarm* contrast ~ 30:1 (the HI ratio is 2.5:1).
- **Popular old idea**: GMCs form by the compression of atomic gas as it crosses ths spiral arms on the time scale of ~ 10^8 yr.
- **Pervasive low-level CO** called “chaff” may account for 10% of the total molecular gas, estimated to be 10^9 $M_{\odot.,}$ but it may not be enough to make GMCs.

CO Emission from Spiral Arms

Heyer et al. ApJS 115 241 1998

The velocity-position diagram (bottom) separates the local and nearby Perseus arms and shows that the CO emission is localized in the arms.

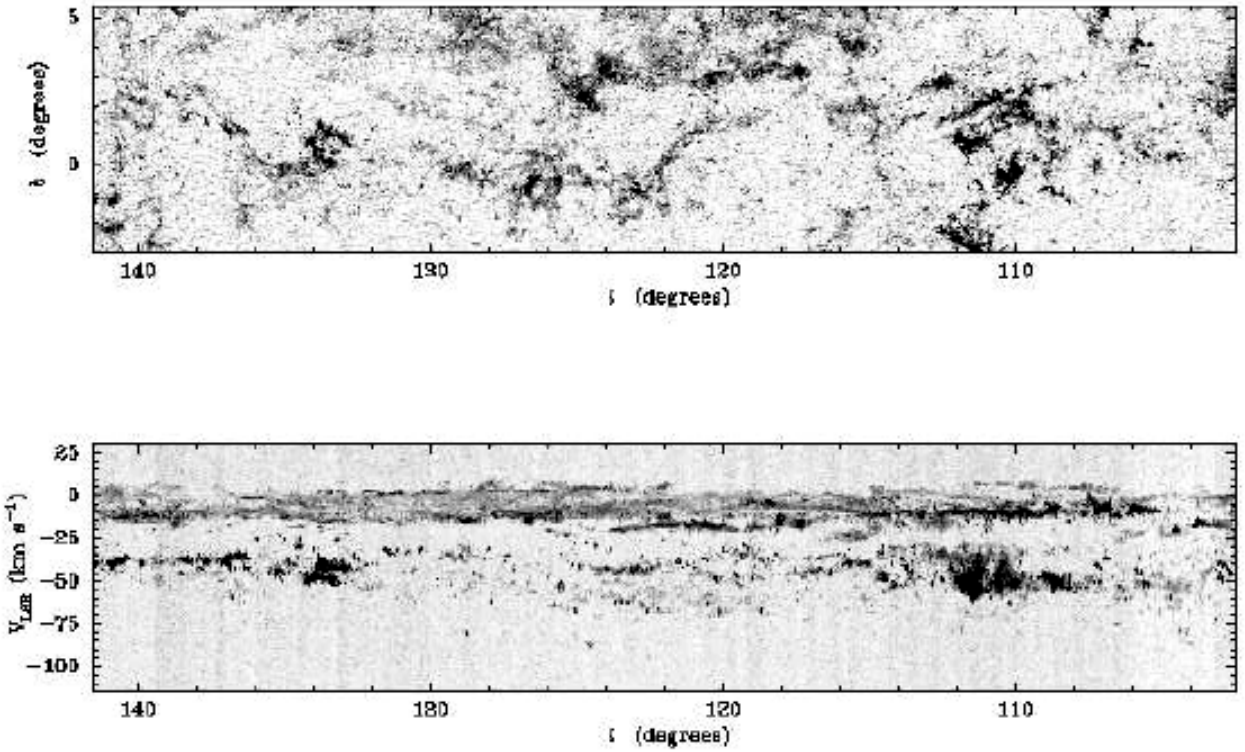
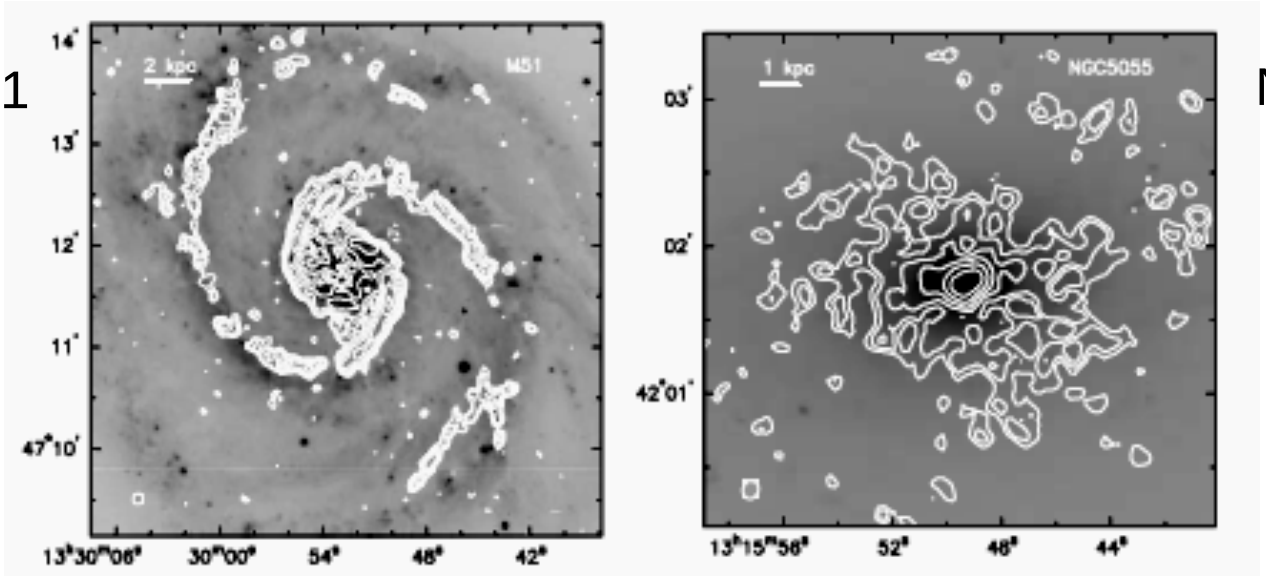


Figure 2. CO emission in the outer Galaxy (from Heyer et al. 1998). Top panel is a velocity integrated $l - b$ plot, lower panel is a $l - v$ plot (integrated over the latitude range of the survey) showing the local and Perseus spiral arms. Note the almost complete absence of molecular gas between the two spiral arms at about 0 – -10 km s^{-1} and -40 km s^{-1}. The high spatial dynamic range of this survey shows the large scale distribution of molecular gas in the ISM in exceptional detail.

GMCs and Spiral Arms

Blitz and Williams (1999)

M 51

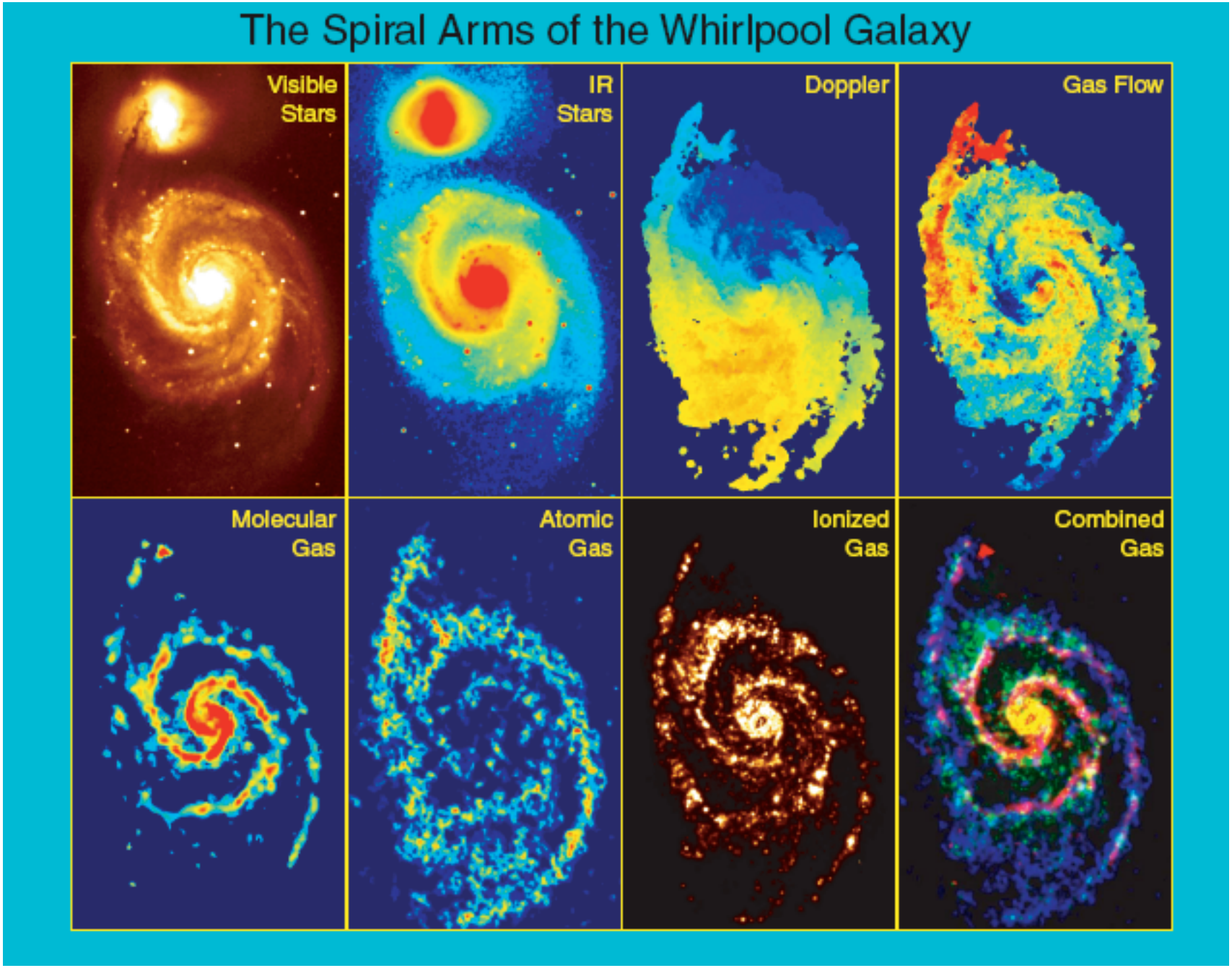


NGC 5055

classic grand spiral weak spiral structure

CO emission overlaid on optical photos

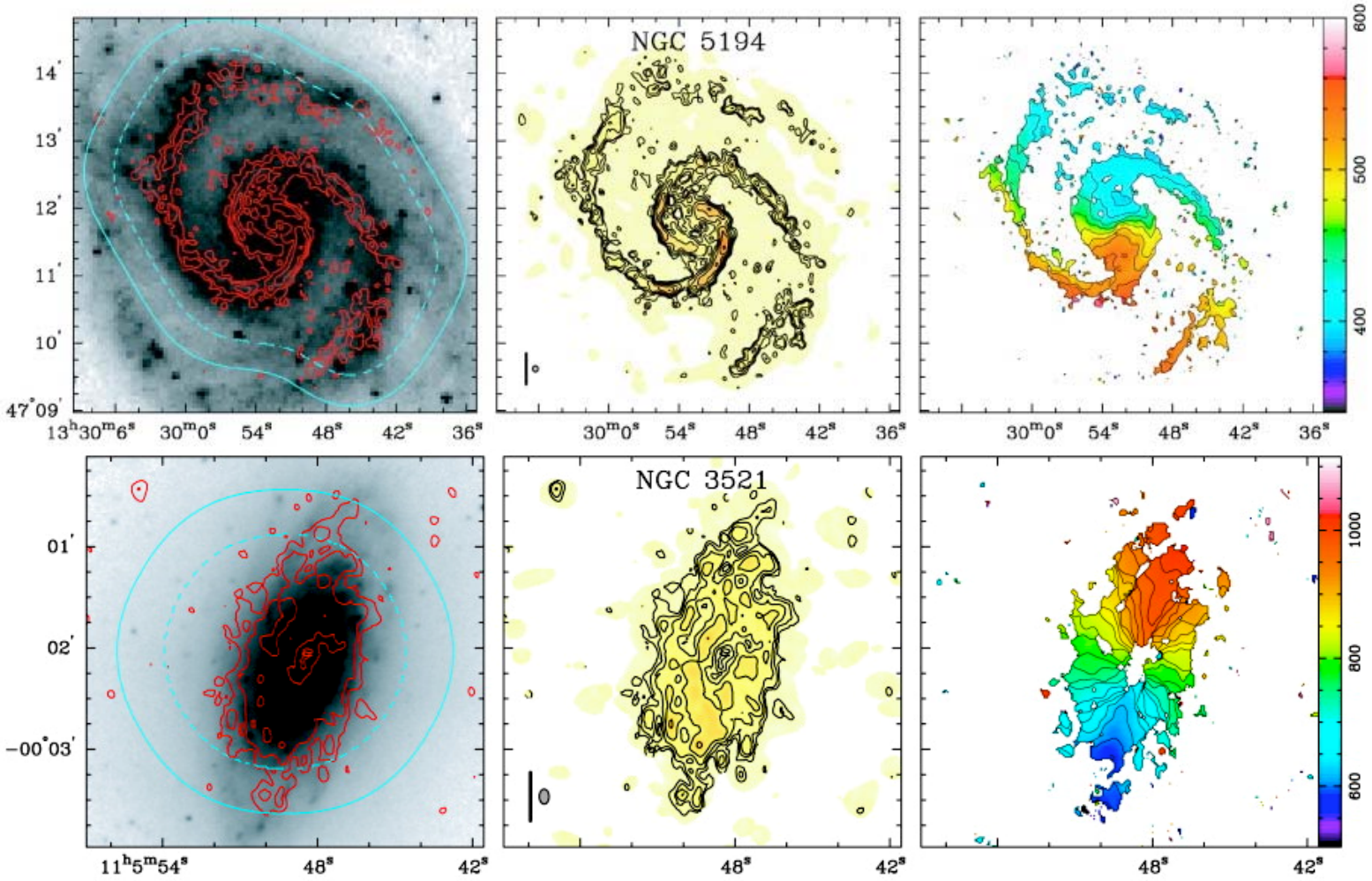
Similar kinds of GMCS in galaxies with and without well-defined spiral structure. How do GMCs form in galaxies like NGC 5055 ?



Courtesy of Leo Blitz

6’’ BIMA CO Survey Of Nearby Galaxies

Helfer et al. 2003 ApJS 145 259

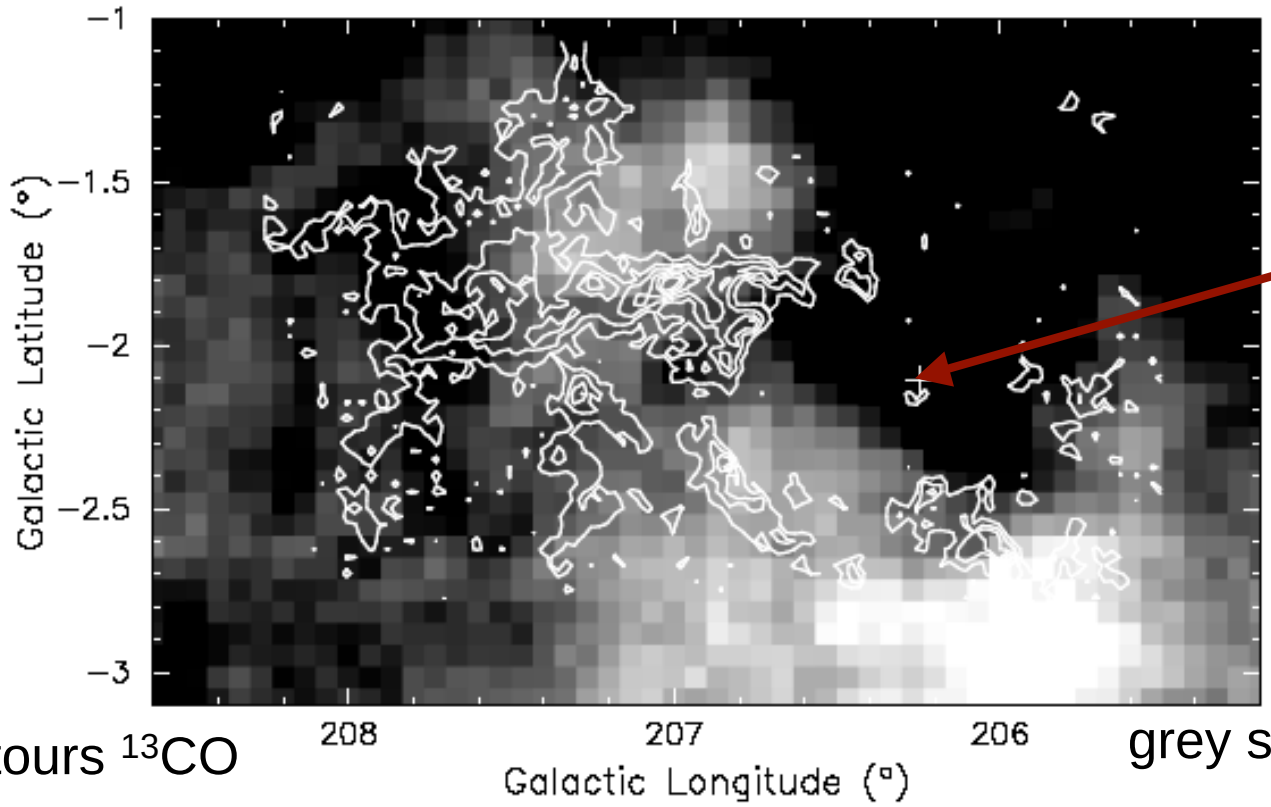


CO emission overlaid on SDSS CO emission CO velocity

2. HI Content of GMCs

- HI envelopes around molecular clouds are common.
- Local GMCs have comparable masses of HI and H_2
- HI is more spatially extended, e.g., 100-200 pc
- Origin of the HI in and near GMCs:
  Photodissociation of H_2?
  Remains of the GMC formation from HI?
- HI properties of GMCs vary throughout the Milky Way, e.g., HI merges into a continuous background in the 5-kpc ring.

HI and ^{13}CO in the Rosette Molecular Cloud



OB ass'n

contours ^{13}CO

grey scale HI

Figure 3. An HI envelope around the Rosette molecular cloud. The grayscale, range 450 to 620 K km s^{-1}, shows HI data from Arecibo observations by Kuchar & Bania (1993). Contours, beginning from and with increment 18 K km s^{-1}, are CO emission from Bell Labs observations by Blitz & Stark (1986). Emission has been summed over a velocity range $v = 4 - 25$ km s^{-1}. The cross marks the OB association that lies at the center of the Rosette nebula and has cleared out the neutral gas. The regions of strong HI emission (lighter colors) lie on the CO cloud boundaries, forming an envelope around the cloud.

Blitz & Williams 1999

3. Formation of Molecular Clouds

An Unsolved Problem

Many processes are involved – gravity, magnetic fields, turbulence, shocks, radiation, etc., but which is dominant?

- Gravity must play a role since GMCs are self-gravitating, but low-mass clouds ($M < 10^3\ M_\odot$) are probably not, e.g., high-latitude clouds and the "chaff".

- GMCs may be short lived, as indicated by the age of the oldest sub-associations (10-20 Myr) that are still associated with GMCs.

- In principle, the age should be greater than the crossing time, but the sound speeds are low. If the large observed line widths reflect MHD turbulence, we can interpret the measured dispersion as the Alfven speed. Applying the line width size relation leads to

$$R/\sigma \sim 2\ \mathrm{Myr}\ (\sigma\ /\ \mathrm{km\ s^{-1}}),$$

somewhat shorter than the above estimtes of the lifetime of a GMC.

Formation Mechanisms

Three ways are often discussed (e.g., Elmegreen in "Evolution of the ISM", ASP 1990)

- Collisional agglomeration of smaller clouds
- Formation from HI, e.g. by "gravo-thermal" instability
- Shocks in a turbulent ISM, generated by outflows from SN remnants

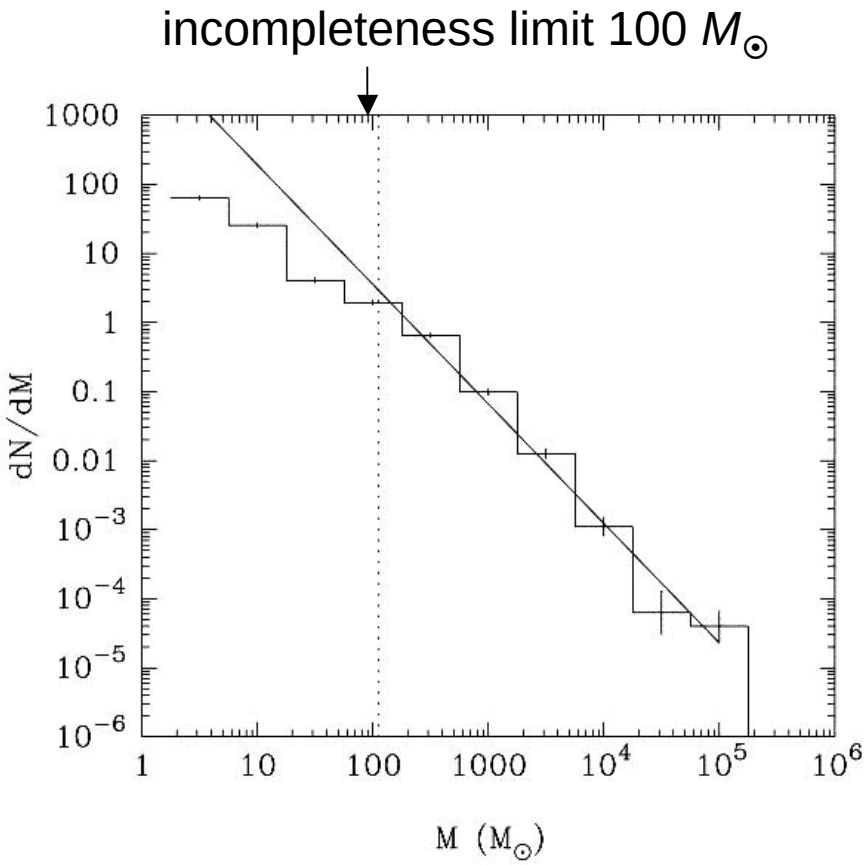
If GMCs are formed from the coalescence (agglomeration) of molecular fragments, where is that gas? Is it the chaff seen in spiral arms and in the vicinity of GMCs? But if star formation has already taken place, would the precursor gas still be observable?

Agglomeration

Heyer & Terebey (ApJ 502 265 1998) catalog ~ 1600 clouds in the FCRAO survey and find $dN/dM \sim M^{-1.75}$.

The single power law says that the non-GMC "chaff" ($M < 10^3\ M_\odot$) appears to belong to the same parent population. Does it have the same origin as self gravitating clouds?

Blitz & Williams argue that the timescales for formation and destructions times are the same order of magnitude (tens of Myr). So in steady state, the mass in low-density molecular clouds and GMCs should be ~ the same. This *not* being the case, they conclude that GMCs form from HI.



4. Structure of Molecular Clouds

CO maps show that molecular gas is heterogeneous.

What is the topology of molecular clouds?

Is it useful to talk about discrete structure?

Blitz & Williams discuss three levels of structure: ***clouds, clumps, and cores***, illustrated by the following maps of the Rosette Molecular Cloud in CO, $C^{18}O$, and CS:

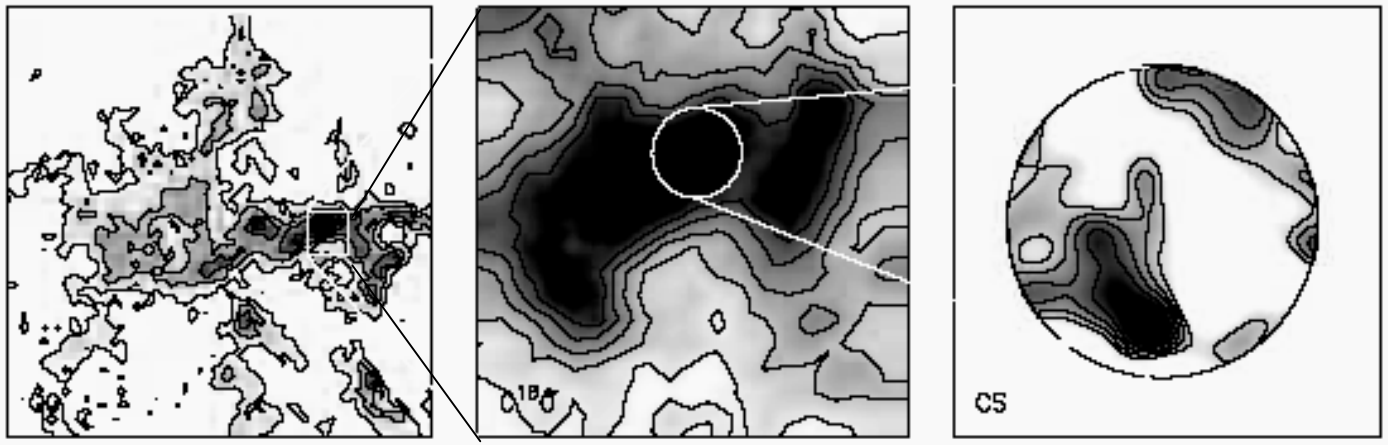


Figure 4. Hierarchical cloud structure. The three panels show a representative view from cloud to clump to core. The bulk of the molecular gas (cloud; left panel) is best seen in CO which, although optically thick, faithfully outlines the location of the H_2. Internal structure (clumps; middle panel) 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″).

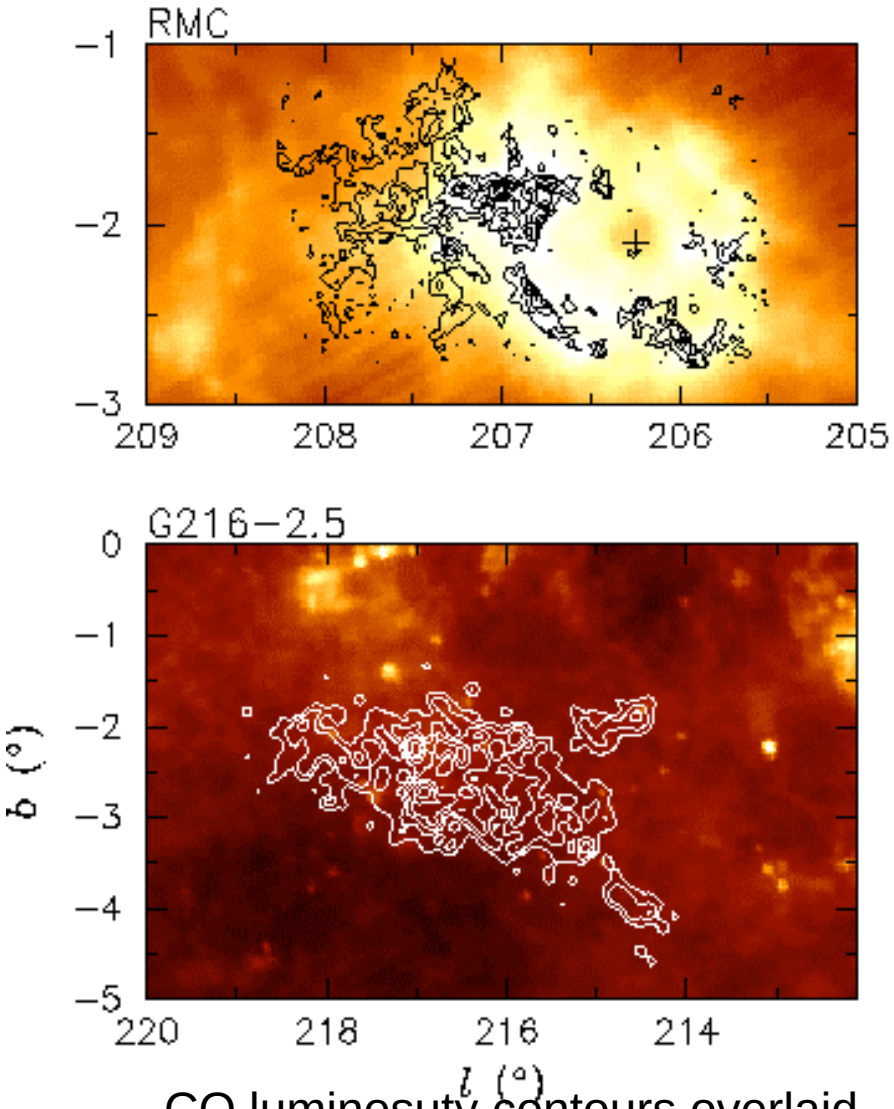
Clumps in GMCs

Williams et al (ApJ 428 693 1994) analyzed the ~ 100 ^{13}CO 1-0 clumps in both the Rosette and the Maddalena Molecular Clouds

Both clouds have similar masses ~ 10^5 $M_\odot$, but orders of magnitude different star formation rates, as traced by FIR dust emission:

- Rosette: ~ 17 OB plus numerous embedded sources
- G216-2.5: no OB stars and low L_{IR} / $M(H_2)$ < 0.07 $L_\odot/M_\odot$
- Star formation in the RMC occurs
- in its gravitationally bound clumps; the MMC has none.

Why is there no star formation in the Maddalena cloud?

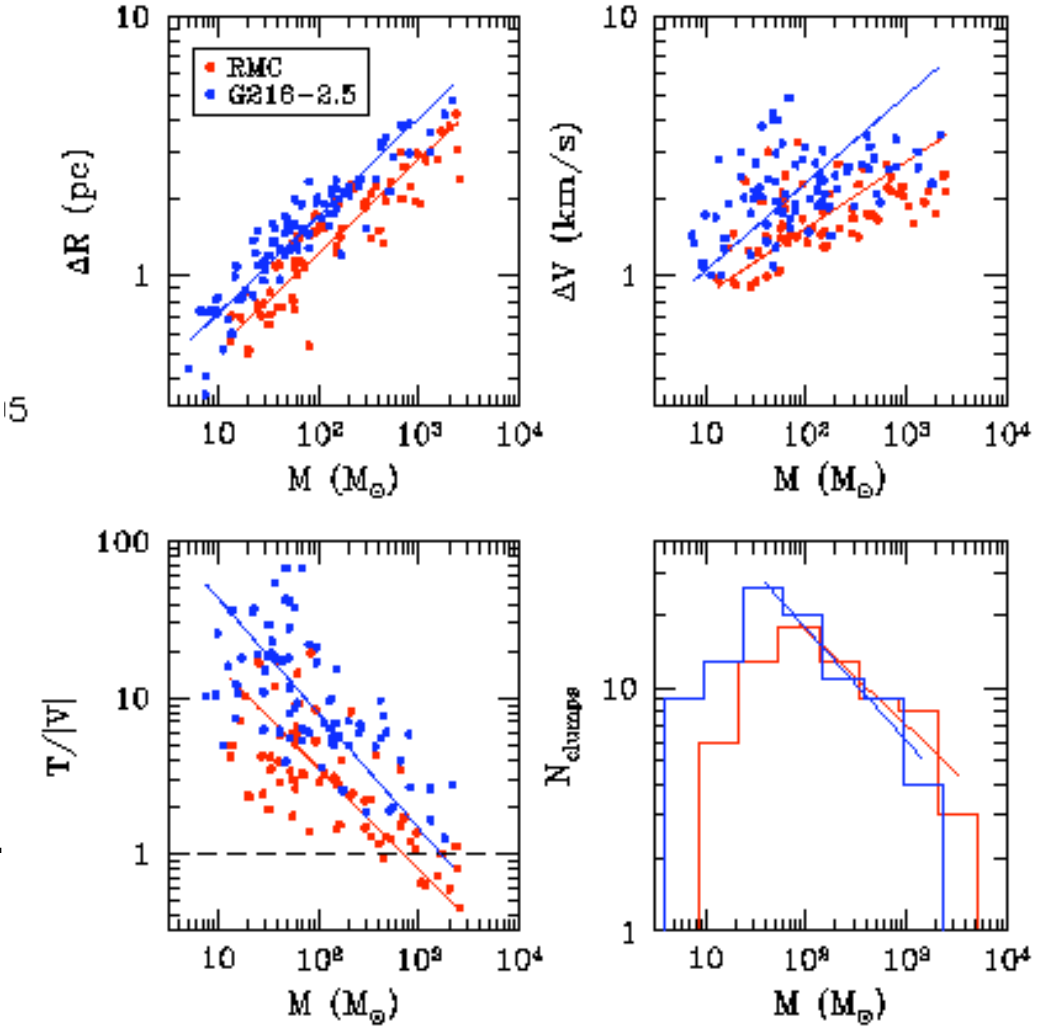


CO luminosuty contours overlaid On IRAS 100 μm intensity

Clump Properties

Williams et al (ApJ 428 693 1994)

- Clump masses derived with an X-factor calibrated with ^{13}CO ~ 1/2 of the galactic average
- Spatial resolution for both clouds is similar ~ 0.7 pc.
- Clumps are more or less similar; those in G216-2.5 are bigger for a given mass and have larger line widths.
- Although both clouds are bound, none of the clumps in G216-2.5 are individually bound.



5. Molecular Cloud Cores

• Star formation is occurs in the densest parts of GMCs known as molecular cloud cores.
• About 1/2 of known cores are luminous IR sources powered by stars in the process of newborn stars.
• Molecular core properties provide the initial conditions for star formation and may determine the properties of the stars they form.
• Keys to observing cores are molecular lines that trace high density rather than low density gas and IR measurements of warm dust heated by newborn stars.

References

Bergin & Tafalla, ARAA 45 339 2007
Benson & Myers, ApJS 71 743 1989
Jijina et al. ApJS 125 161 1999

Dense Gas Tracers

Molecule	Transition	Frequency (GHz)	E/k (K)	n_{crit} (cm^{-3}) @ 10 K	n_{eff} (cm^{-3}) @ 10 K
CS	1-0	49.0	2.4	4.6×10^4	7.0×10^3
	2-1	98.0	7.1	3.0×10^5	1.8×10^4
	3-2	147.0	14	1.3×10^6	7.0×10^4
HCO^+	1-0	89.2	4.3	1.7×10^5	2.4×10^3
	3-2	267.6	26	4.2×10^6	6.3×10^4
HCN	1-0	88.6	4.3	2.6×10^6	2.9×10^4
	3-2	265.9	26	7.8×10^7	7.0×10^5
H_2CO	2_{12}-1_{11}	140.8	6.8	1.1×10^6	6.0×10^4
	3_{13}-2_{12}	211.2	17	5.6×10^6	3.2×10^5
	4_{14}-3_{13}	281.5	30	9.7×10^6	2.2×10^6
NH_3	(1,1)	23.7	1.1	1.8×10^3	1.2×10^3
	(2,2)	23.7	42	2.1×10^3	3.6×10^4

See Schoier et al. A&A 432 369 2005 for dipole moments etc.

Measurement of Core Temperatures

Although almost any optically-thick rotational ladder may work, the ***inversion spectrum*** of NH_3 is the most useful. The basic reference is Townes & Schawlow, Ch. 12.

In the ground state, the N atom Is located on either side of the 3 H atoms in the plane. To get to the other side, it has to tunnel through the potential barrier, whose height is ~ 2,000 cm^{-1}. The tunneling frequency is very small and is in the cm radio band.

Similar splittings occur for methanol (CH_3OH).

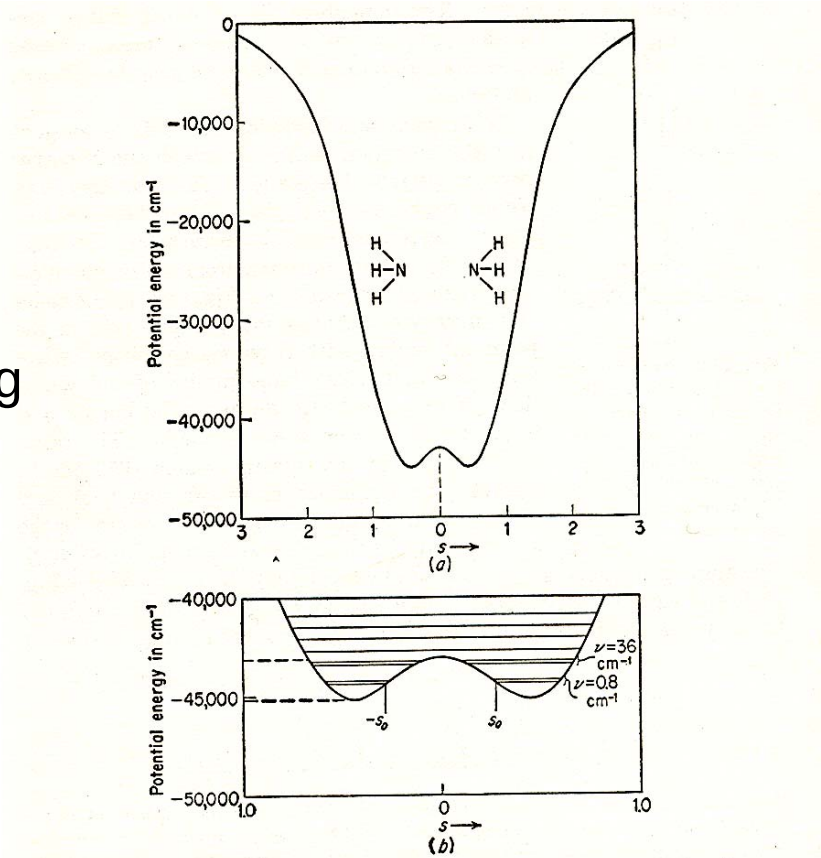


FIG. 12-1. Potential curve of NH_3. The variable s is a measure of the distance between the nitrogen and the plane of the hydrogens. (*b*) shows the lower part of the potential curve in more detail, and the energy levels.

NH_3 Temperature Measurement

NH_3 is a symmetric rotor with a dipole moment of 1.48 D.
The allowed *rotational* transitions satisfy $|\Delta J| = 1$ and $\Delta K = 0$,
but the frequencies are so high they require space observations.

But the levels are split by tunneling in the 25-GHz band that depends on (J,K). The transitions usually observed are at the bottom of each K-ladder. The splittings of these (K,K) levels are:

(1,1)	23.694 GHz
(2,2)	23.723
(3,3)	23.870
(4,4)	24.139
(5,5)	24.533
(6,6)	25.056

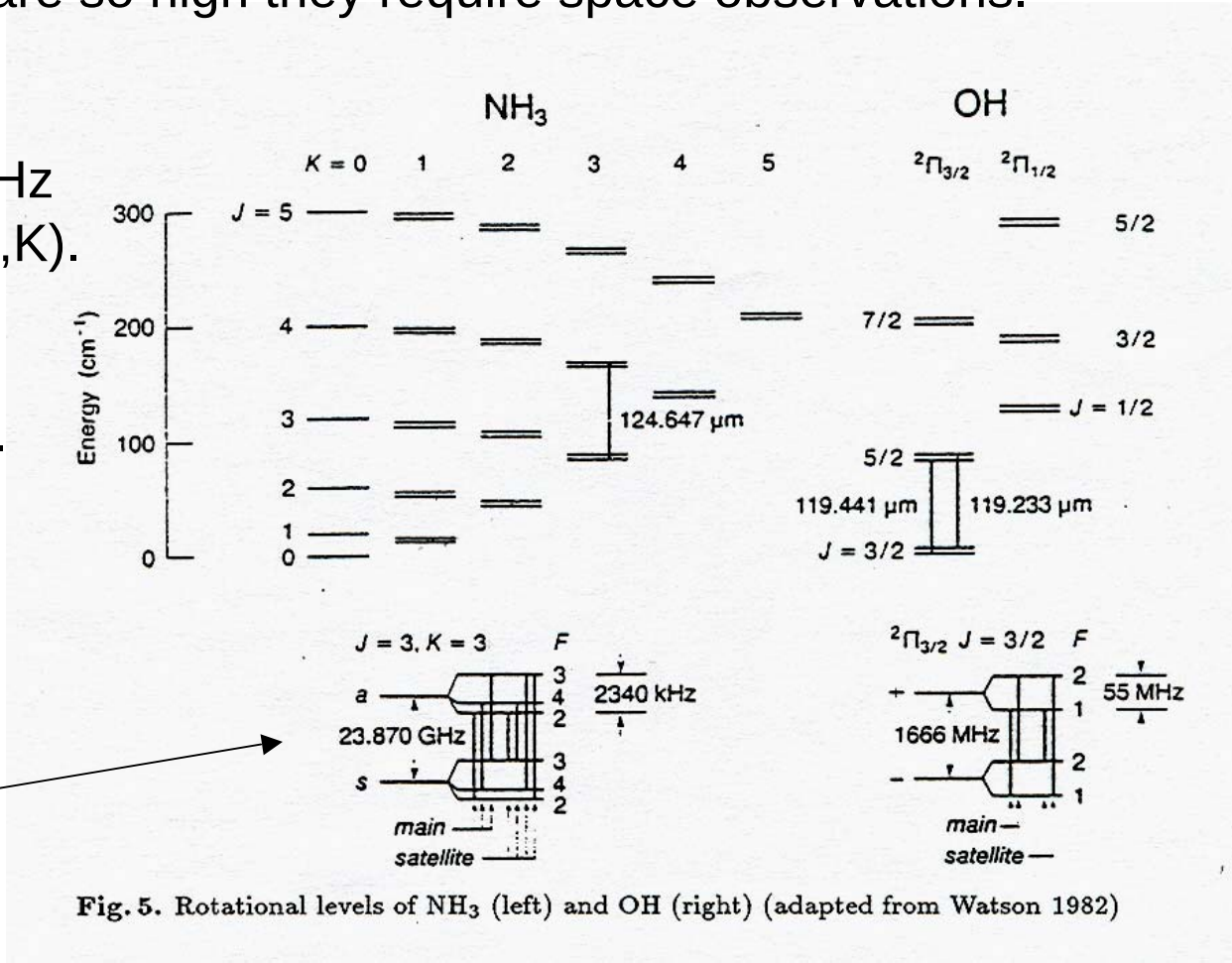


Fig. 5. Rotational levels of NH_3 (left) and OH (right) (adapted from Watson 1982)

The hyperfine splittings are also shown.

NH_3 Temperatures

The beauty of measuring the inversion transitions of the NH_3 (*K,K*) levels is that they span a large range of excitation temperature but require measurements in just one radio band (using the same instrumentation for all transitions). The transitions listed above cover the temperature range up to 500 K.

This is to be contrasted with a non-hydride rotor like CO where a large range of excitation temperatures can only be achieved by using different telescopes with different resolution.

The often used (J,K)=(1,1) level occurs at 1.27 cm and has a fairly high critical density.

Shapes of Molecular Cloud Cores

Lada et al. 376 561 1991

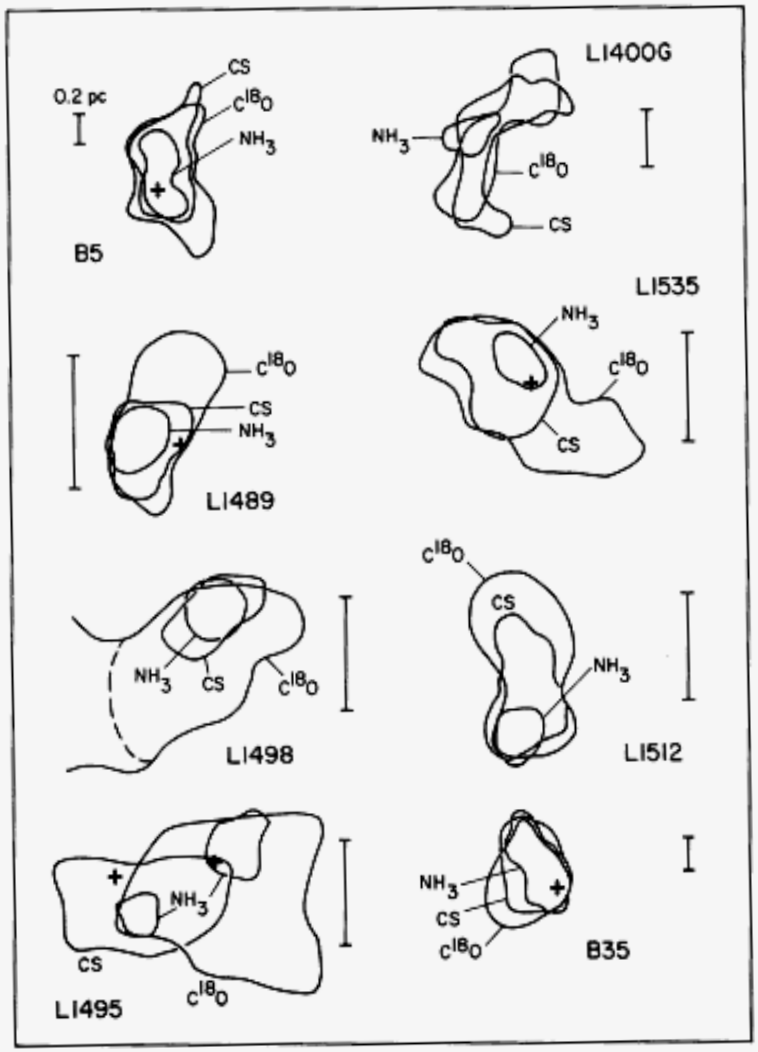


FIG. 1a

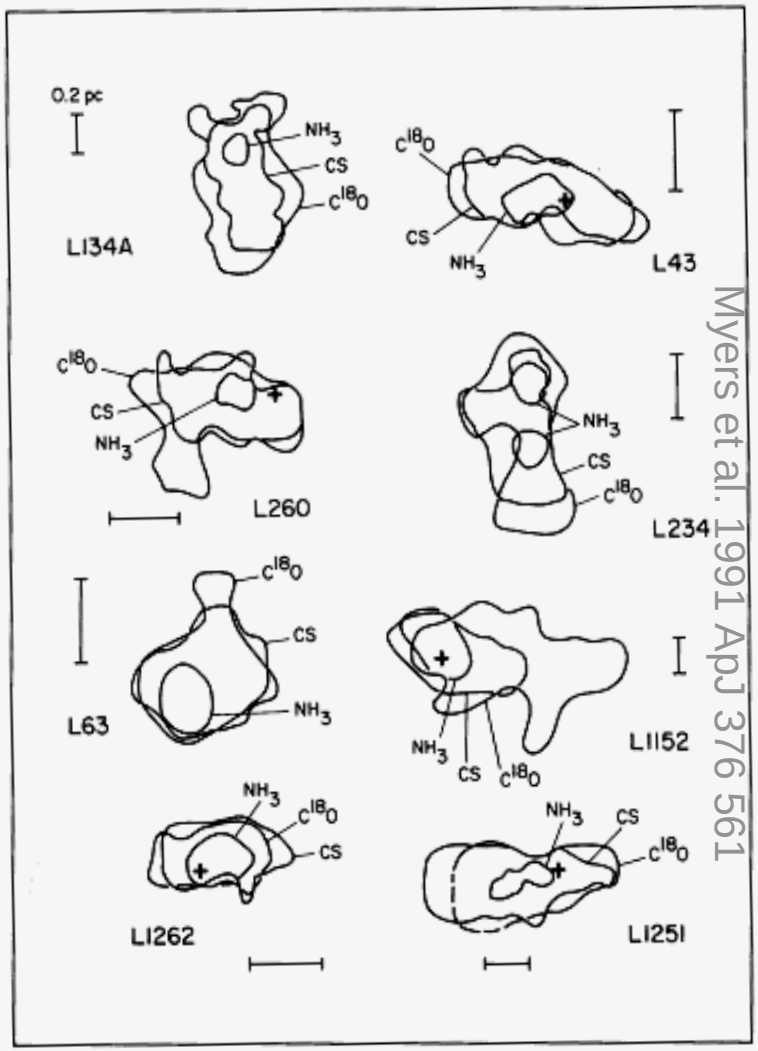


FIG. 1b

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

Notice the different map sizes for CO, CS & NH_3

Survey of 264 NH_3 Cores

Jijina et al. (ApJS 126 161 1999)

NH_3 Column Radius Aspect Ratio

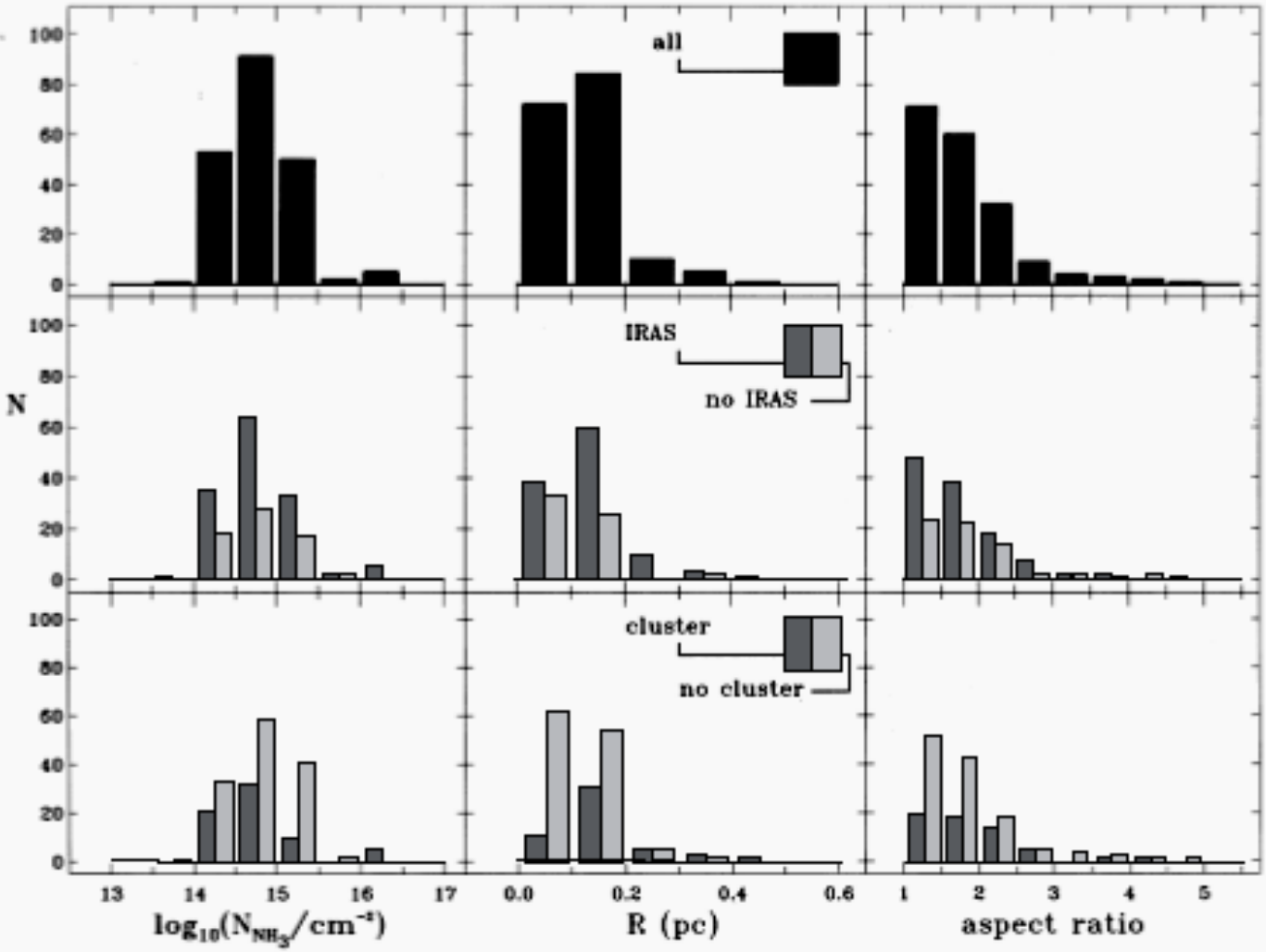


FIG. 1.—Distributions of the core gas properties: column densities, N_{NH_3} (cm^{-2}), core sizes, R (pc), and aspect ratios, q/h, for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

Jijina et al. NH_3 Core Survey

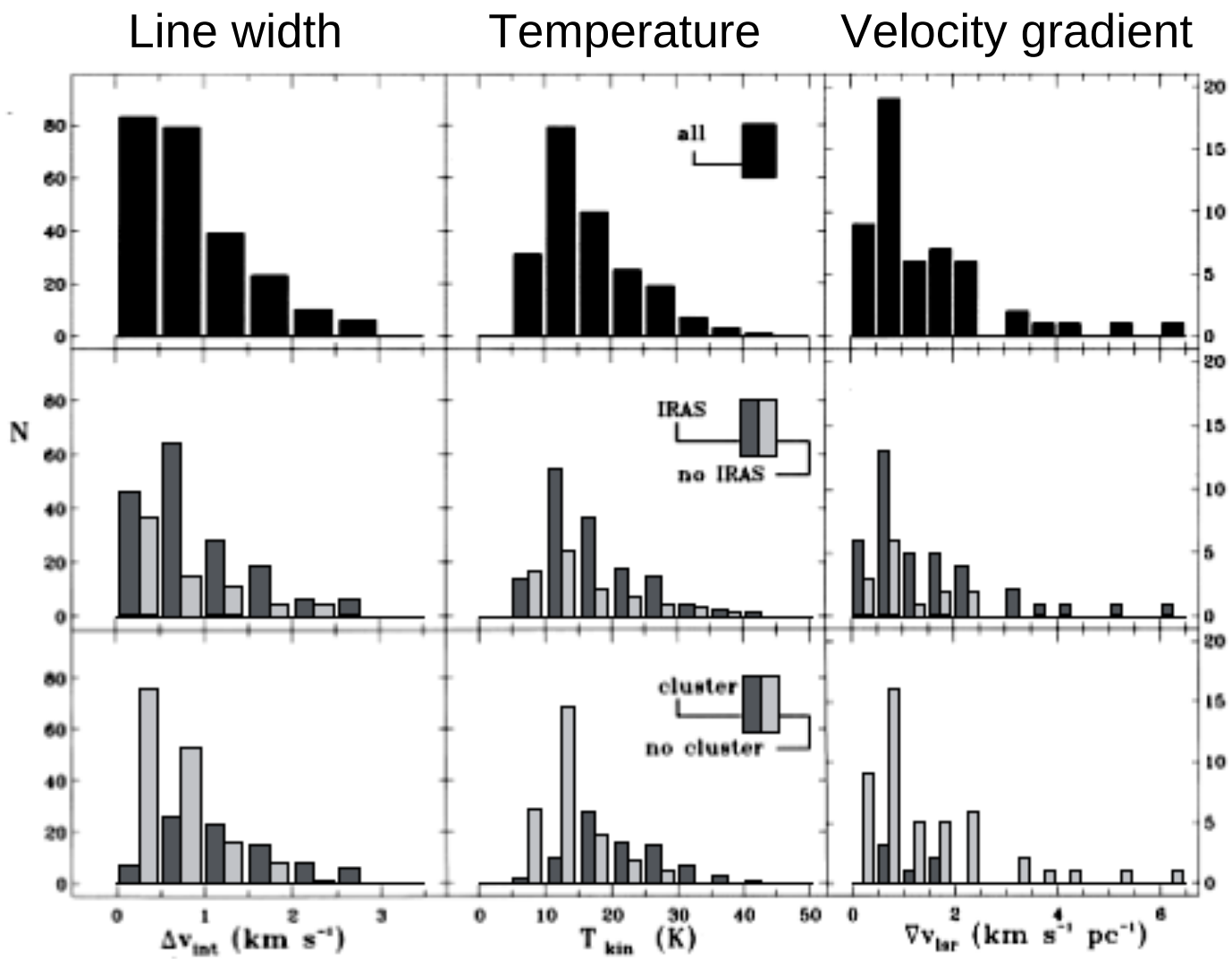


FIG. 2.—Distributions of the core gas properties; intrinsic velocities, Δv_{int} (km s^{-1}), kinetic temperatures, T_{kin} (K), and velocity gradients, ∇v_{lsr} (km s^{-1} pc^{-1}), for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

Jijina et al. NH_3 Core Survey

Mass distribution

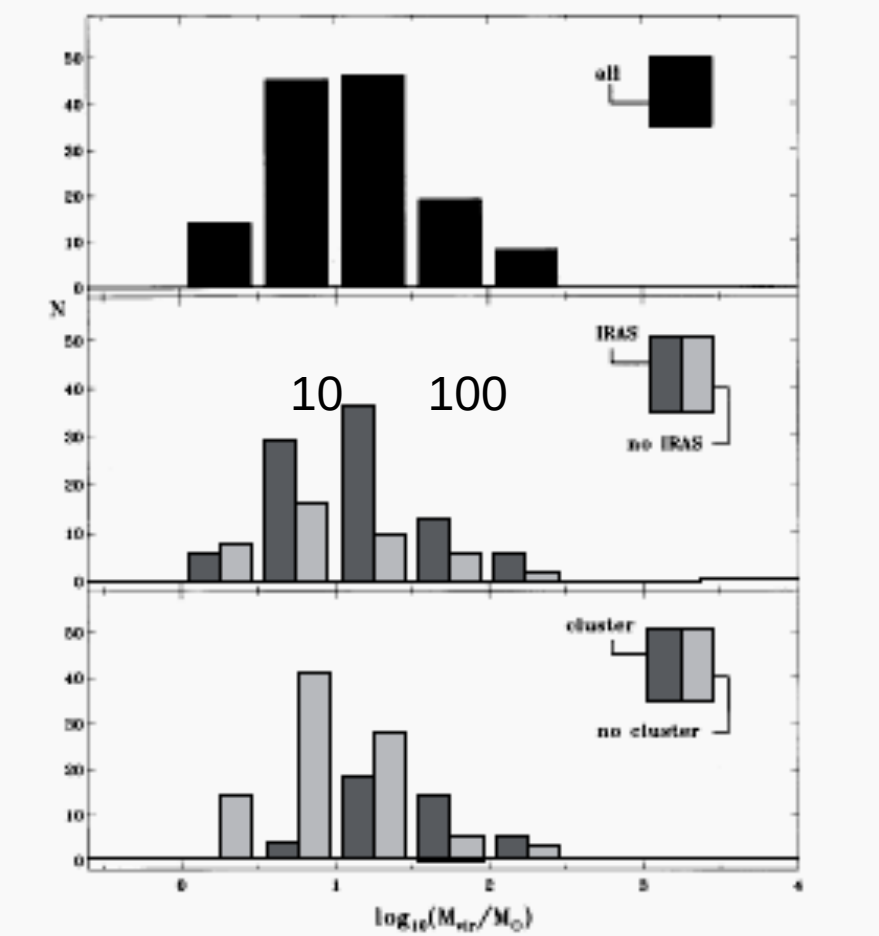


FIG. 3.—Distributions of the core mass distribution, $M_{vir}/M_\odot$, for the sum total sample containing all cores as well as for subsamples defined by the *IRAS* and cluster criteria. Refer to Tables B1–B3 for the statistics and to § 3 for a discussion.

Observed Core Properties

1. associated with star formation, e.g., 50% or more have embedded protostars (SPITZER has found a few more)

2. elongated (aspect ratio ~ 2:1)

3. internal dynamics may be dominated by thermal or turbulent motion,

$$\Delta v_{\rm FWHM}{}^2 = \Delta_{\rm turb}{}^2 + 8 \ln 2 \, (\frac{kT}{m})$$

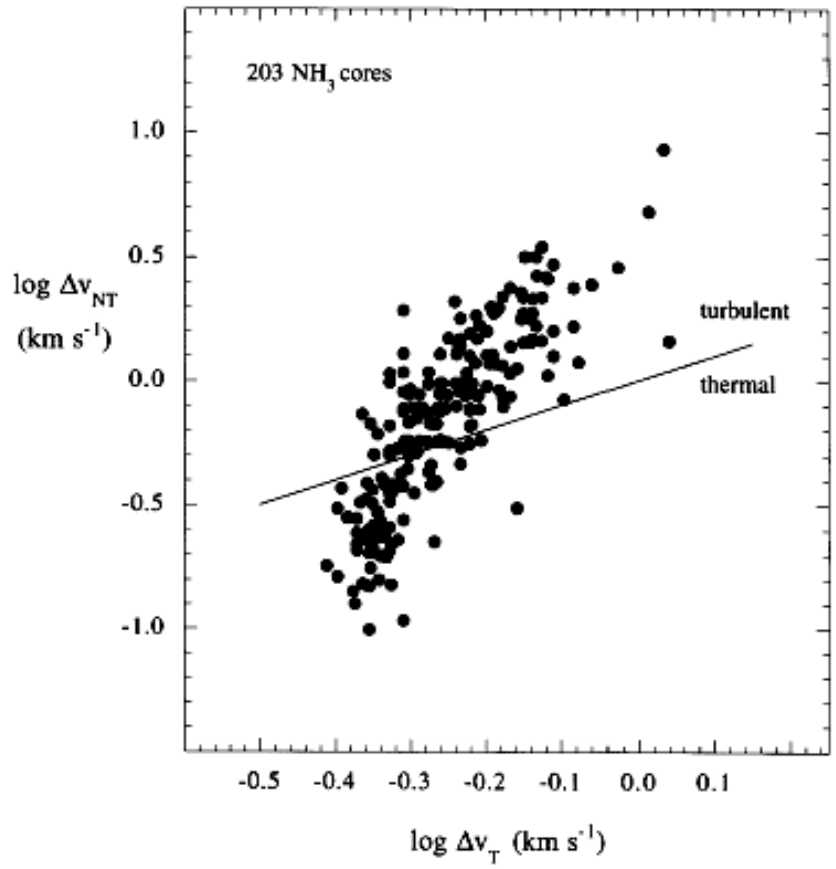
e.g., equally split for NH_3 cores. Note that

$$\Delta v_{\rm th} = \sqrt{8 \ln 2 \, (\frac{kT}{m})} = 0.675 \, {\rm km \, s^{-1}} \sqrt{\frac{m_{\rm H}}{m} (\frac{10 {\rm K}}{T})}$$

is typically ~ 0.1 – 0.2 km s^{-1}

Non-thermal vs. Thermal Line Widths

Non-thermal



thermal

Figure 6. **Nonthermal and thermal line widths in NH_3 dense cores. The FWHM of the distribution of nonthermal motions, Δv_{NT}, increases rapidly with the corresponding FWHM of the distribution of thermal motions of the molecule of mean mass, Δv_T. Thus turbulent cores tend to be warm, and quiescent cores tend to be cool (JMA).**

Jijina et a. ApJS 126 161 1999

Observed Core Properties

4. temperature: T ~ 10 – 20 K

5. size: R ~ 0.1 pc

6. ionization: $x_e \sim 10^{-7}$

7. size-linewidth relation
   $R \sim \sigma^p$, p = 0.3-0.7

8. approximate virial equilibrium

9. mass spectrum: similar to GMCs.

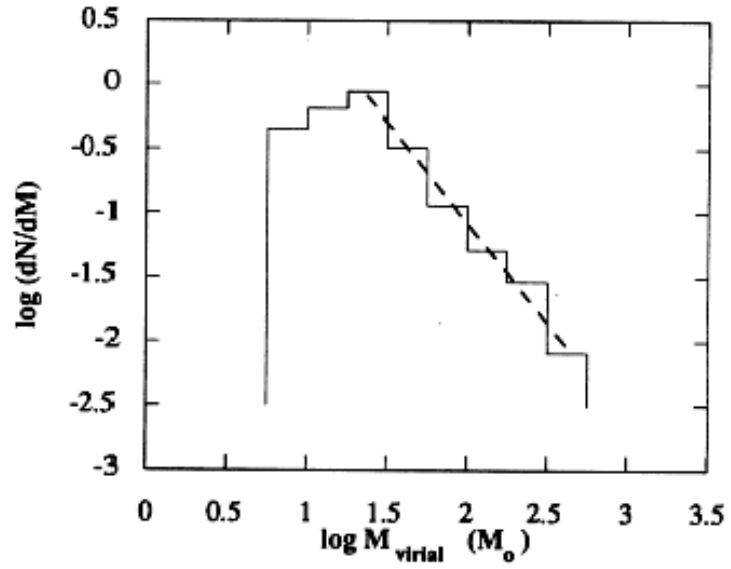


Figure 6. The mass spectrum of dense cores in the L 1630 cloud from the study of LBS. The spectrum can be characterized by a power law with an index of -1.6.

fact that different definitions of clumps were employed in each case [20, 122].